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Estrategias operativas óptimas para servicios feeder en primera/última milla debido a la llegada de vehículos autónomos

Caso de estudio: áreas suburbanas alrededor de los corredores de tunnelbana, pendeltåg y lokalbana en Estocolmo

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Optimal operating strategies for first/last mile feeder services due to the arrival of automated vehicles

Case study: suburban areas around tunnelbana, pendeltåg and lokalbana corridors in Stockholm

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Abstract

With the improvements of the vehicle technology related with connectivity, sharing, automation and electrification and as a solution to the problems that cities are facing, such as an intense population growth and pollution, there are new forms of mobility that are or will be created within the framework of the future mobility. In this context, the arrival of driverless autonomous vehicles will provoke an irreversible change supporting the implementation of new forms of mobility or improving the existent. One factor that will help to do feasible the improvement of the existent mobility is the reduction of costs due to the arrival of autonomous vehicles, what will make on-demand transportation competitive under certain circumstances when comparing costs between it and fixed route systems. This thesis studies for the case of the metro/rail corridors in the metropolitan area of Stockholm which areas are suitable to implement Demand Responsive Transport (DRT) according to urban configuration and access to transit parameters. Once the identification is done, a model to compare between two different operating strategies for feeder services is applied to obtain which one is optimal under different stages of development of the technology related with the vehicles in the fields of automation and electrification. The model used, with additions to existing ones to adapt it to the use of it to real scenarios, gives numerical results for the four considered stages, showing the importance of the travel demand and the street sinuosity on the results and selection of the optimal. The method and criteria developed contributes to have a clear identification of the areas in which the implementation of the DRT services would be feasible in a future mobility scheme.

Keywords

public transport · autonomous vehicles · demand responsive transport · future mobility · suburban areas · operation strategies · costs evaluation

Sammanfattning

Med förbättringarna av fordonstekniken relaterad till sammankoppling, delningstjänster, automatisering och elektrifiering och som en lösning på de problem som städer står inför, till exempel en intensiv befolkningstillväxt och förorening, finns det nya former av rörlighet som skapas eller kommer att skapas inom ramarna för den framtida rörligheten. I detta sammanhang kommer ankomsten av förarlösa autonoma fordon att leda till en oåterkallelig förändring som stöder implementeringen av nya former av rörlighet eller förbättrar de existerande. En faktor som hjälper till att möjliggöra en förbättring av den befintliga rörligheten är minskningen av kostnaderna sedan autonoma fordon har börjat användas, som kommer att göra efterfrågestyrda transporter konkurrenskraftiga under vissa omständigheter när man jämför kostnader mellan det och fasta ruttsystem. Detta examensarbete studerar fallet med tunnelbana/järnväg korridorerna i Stockholms storstadsområde, vilka områden som är mottagliga för att genomföra *Demand Responsive Transport* (DRT) enligt stadskonfiguration och tillgång till transitparametrar. När identifieringen är klar tillämpas en modell för att jämföra två olika driftsstrategier för matartjänster för att ta reda på vilken som är optimal under olika utvecklingsstadier av tekniken relaterad till fordonen inom områdena automatisering och elektrifiering. Modellen som används, med tillägg till befintliga modeller för att anpassa den till användningen av den till verkliga scenarier, ger numeriska resultat för de fyra övervägda stadierna, vilket visar vikten av efterfrågan på resor och gatans kurvighet på resultaten och valet av det optimala. Metoden och de kriterier som utvecklats bidrar till att ha en tydlig identifiering av de områden där implementeringen av DRT-tjänsterna skulle vara möjlig i ett framtida mobilitetsprogram.

Nyckelord

kollektivtrafik · autonoma fordon · efterfrågestyrda transporter · framtida rörlighet · städer förorter · operativ strategi · kostnadsbedömning

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Stockholm, tack så mycket för allt och alla
València, moltes gràcies per tot i per tots

Alberto Romero López
Stockholm, 2020

List of figures

List of tables

INDEX

1. Introduction

Cities all over the world are facing several problems shared by some of them and more or less serious depending on the conditions and the level of development of the city and the country. One of these problems and challenges to face is the non-sustainable transportation, or not as sustainable as it should be, which consequences goes from the effects of the CO2 and the other greenhouse gasses on the climate change to the effects related with the health of the people that suffers problems related with the quality of air and pollution, such as asthma, bronchitis, leukaemia and lung disease (Banister, 2007).

One of the causes of that pollution and its related problems is the mode of transportation of the residents of the cities, cities which are continuously growing. Having more sustainable transportation, switching from private modes to public can directly reduce the emissions of greenhouse gases, improving the situation in terms of climate change and the health of the citizens.

The mentioned one is just one of the multiple problems faced by the cities nowadays regarding people mobility and transportation accessibility. The solution to some of those problems can be the new forms of mobility that are or will be created within the future mobility framework thanks to the technology improvements in terms of connectivity, sharing, automation and electrification.

The arrival of driverless autonomous vehicles will provoke an irreversible change from the conventional public transport that it is known nowadays to a plausible vision of the public transport system in which the multimodality will be strengthened between the trunk lines with conventional public transport and different kinds of new mobility using autonomous vehicles acting as a component of that integral system, as authorities like the International Association of Public Transport (UITP) proposes. These automated vehicles would have different operational strategies, used as feeders to public transport, area-based on-demand autonomous mini-buses, autonomous car-sharing systems, or a swarm of autonomous vehicles as robotaxis and on-demand shuttles.

That mentioned change would be possible due to the reduction of the current operating costs derived from the improvements in the field of automation (especially due to the reduction of drivers) but also in the field of electrification (due to the more efficient energy consumption).

Nowadays due to the limitations of the technology, some of the mentioned future mobility services are not competitive versus conventional services. The area-based on-demand autonomous mini-buses are basically a demand responsive transport (DRT) using autonomous vehicles. DRT is a service that already exists but that are largely limited to specialized operations such as taxicabs, shuttle vans, dial-a-ride services, and paratransit services. DRT is a flexible transit service operating in a demand responsive mode within an area, moving passengers to a transfer point that connects within a fixed route of major transit network. That desired flexibility offering the door-to-door services makes DRT much more costly than the fixed-route transit (FRT). FRT are more cost efficient because of the predetermined schedule, the large loading capacity of the vehicles and the consolidation of many passenger onto a single vehicle but, on the other hand, they present the problem of lack of flexibility not matching the rider’s desires.

The switch between the FRT and DRT would be possible when a certain level of automation is achieved and the electrification technology is improved as well, and with it the reduction of costs, that will make the on-demand transport more competitive than the fixed one. The areas in which the applicability of this type of transportation are still very reduced, but with the cost reduction mentioned, the number of areas in which it would be possible to implement this kind of service with competitiveness is higher.

Some of these prototypes of autonomous vehicles are being tested in serval cities, with a purpose in some of them of implementing them as an area-based on-demand service in a near future. The definition of areas in which the implementation of this type of service would be plausible social and economically is important for having a good starting point for the future mobility.

1.1. Scope of study

The project has two different scopes, as the first one is for the selection of the zones studied, that will be analysed individually in a more detailed level.

The first scope of study is the Stockholm county (*Stockholms län*), where the Stockholm Public Transport (*Storstockholms Lokaltrafik*, SL) runs its services of public transport as the commuter rail (including tunnelbana, pendetåg and lokalbana) corridors in the suburban area of Stockholm. These commuter rail services are owned by SL although there are different contractors that operates the services.

The county is divided into zones according to the division of the Regional Development Plan for the Stockholm Region (*Regionala utvecklingsplan för Stockholmsregionen, RUFS)*

FIGURE 1. Stockholm county with the zone division from the *Regionala utvecklingsplan för Stockholmsregionen* - RUFS

The second scope is defined by the zones resultant from the selection from the first scope, in order to be analysed with detail, a detail with a size-level similar to the one in the zone division of the figure 1. The selection of these zones will follow a certain procedure explained in detail later in this document, being all of them suburban areas around the commuter rail corridors. The description in detail of all of these areas can be found in Appendix A of this document.

1.2. Aims and objectives

The main research questions that pretend to be answered through the realisation of this project are:

In case of the necessary development to have a demand responsive transport as a competitive operating solution for feeder services in suburban areas, which areas in Stockholm would be suitable to implement it? And, in which areas would the DRT the optimal operating strategy? Is it possible to consider that an analytical model is able to give results that represents real cases?

The questions mentioned leads to the definition of aims and objectives to achieve with the realisation of the project, that are:

- Selection of suburban areas around the rail corridors in Stockholm in which there is suitability to implement demand responsive transport services
- Improvement or extension of an existing analytical model and validation of it with a simulation
- Determination of the optimal operation strategy in the selected areas with the use of the mentioned model

The structure of this report includes the research, the methodology followed, results obtained and its discussion and the conclusions that can be extracted. In the next section, there is an extensive review of literature about future mobility, automation, and feeder solutions for first/last mile solutions. After it, in section 3 the development of the city of Stockholm and its relationship with the development of its public transport network is exposed.

In sections 4, 5 and 6, the methodology, application to a case study and the analysis of the results are shown separately for each section. Section 4 presents the selection of the zones that are suitable to implement services of DRT according to the procedure described in it. The description of an analytical model and its evaluation to study the applicability of the operating systems in the zones selected previously is carried out in section 5. Section 6 leads to give a validation with a commercial software of the results given in the analytical model with an idealised zone and to evaluate the results of implementing a DRT service in the areas mentioned as suitable in the commercial software chosen. Finally, in section 7 the conclusions and future work are presented.

2. Literature review

The purpose of this section is, through the review of previous work, to develop a basis for the execution of the work done in this project and to answer the research questions laid out previously. This literature review is based on articles, papers, books, or other research work existing about the future mobility, automation, and feeder solutions for first/last mile solutions.

The mobility in the cities is experimenting a change and the new technologies developed in the ambit of transportation are already playing a key role shaping how people will move in the cities (Arthur D.Little, 2018).

There are four main trends in terms of technology that will shape the future of urban mobility, being them the connectivity, sharing, automation, and electrification (Hannon, Knupfer, Sebastian, Sumers, & Nijssen, 2019). According to the improvements in the vehicle technology, two main fields have been developed during the last years, the automation and the electrification, being them described more in detail due to its effects on the variation of the cost structure.

The connectivity, through the development of the technology and the Internet of Things (IoT) will help to improve the actual services provided, making them more efficient, or implementing new forms of travelling, incorporating them to the network, improving the mobility and the accessibility in the cities.

Sharing solutions is one of the services that have been already growing due to the improvements related with the connectivity, with services such as carsharing or bike sharing. The behavioural change in terms of mobility with the inclusion of shared vehicles is agreed to seem irreversible (Frost & Sullivan, 2015) and the carpooling variants are forecasted to gain share in the market of transport services, implying that using a virtual device for requesting a service to pick-up passengers will become more and more common in future mobility scenarios.

The automation of the vehicles is still in process of being fully developed to achieve the complete self-driving, with some trials being currently carried out in experimental areas.

TABLE 1. Automation levels of vehicles given by the Society of Automotive Engineers (SAE, 2018)

level	name	capabilities
0	no automation	No autonomy, being the driver performing all the tasks
1	driver assistance	Some driving assist features, being the vehicle controlled by the driver
2	partial automation	Vehicle has combined automated functions (such as acceleration and steering), being the vehicle controlled by the driver
3	conditional automation	The driver is not required to monitor the driving environment but is necessary, being ready to take control of the vehicle in any moment with notice
4	high automation	Under certain conditions the vehicle can perform all the driving functions while the driver may have the option to control the vehicle
5	full automation	Under all conditions the vehicle can perform all the driving functions while the driver may have the option to control the vehicle

The Society of Automotive Engineers (SAE) has classified the different levels of automation that the vehicles can offer, what can be used as a good guideline of the different stages between the conventional vehicle and the autonomous vehicle. (SAE, 2018) classifies the levels of automation of vehicles as it is shown in Table 1.

The electrification of the road traffic is relatively new (especially if its compared with the electrification of the rail transport) but the technology available in the market is quite advanced, giving some advantages as their fewer GHG emissions, no contribution to smog or no noise emitted, although with some handicaps specially due to the level of development of the batteries and the autonomy of kilometres of the vehicles. The numbers still show a tiny share of electric vehicles as in China, world leader on it, the electric vehicles sold in 2016 were just 30% of the total (Hannon, Knupfer, Sebastian, Sumers, & Nijssen, 2019) but the tendency on this ambit is to increase the usage and implementation of electric vehicles.

Cities are a complex dynamic system in which the mobility is one of its components, suitable to experiment changes that lead to new concepts on mobility driven by the four technology trends explained previously. Some of the changes in that ambit of the new mobility and that can be seen as a potential solution to some of the problems in the cities not coming just from the technology but also from the way that technology is used, are (Barceló Bugeda, Montero Mercadé, & Ros Roca, 2018):

- Shift from the vehicle ownership to vehicle usage due to the social changes of the relation between automobiles and humans.
- The concept of the multiple passenger trip-sharing based on flexible transportation under the concept of a service with Demand Responsive Transport (DRT) what will lead to new concepts in the scope of public transportation.
- The applications of Information and Communication Technologies (ICT) making possible to conceive the concept of mobility as a service (MaaS) with applications for the user to plan and manage the trips dynamically as well as the utilization of that information to provide to the user the needed service when and where it is needed.

As it has been described for the automation and electrification, these two fields of improvement of vehicle technology are still not fully developed and there are several obstacles before their full implementation. The changes in these technology trends, together with connectivity and sharing, will affect to the mobility with the change of behaviour or apparition of new concepts of mobility, in part thanks to the reduction of their cost structure. This reduction of the cost structure comes along with significant changes in different directions, such as the ones included with the future mobility, that will lead to changes in road capacity, urban space consumption, vehicles kilometre travelled, safety, less pollution, energy consumption or efficiency (Badia & Jenelius, 2020a and 2020b), among others.

The reduction of the costs will be due to the automation and the electrification although the biggest change is due to the former. The automation can reduce the operating costs significantly due to the elimination of the driver, what represents a high percentage over the total of the costs, representing in the case of bus systems up to the value of the 55% of the total cost according to the Swiss Federal Office for Transport (Bundesamt für Verkehr, 2011) or around the 40% of the total cost according to the Australian Transport Council (ATC - Australian Transport Council, 2018). In the case of taxis, the reduction of the costs can be up to the 88% (Bösch, Becker, Becker, & W.Axhausen, 2017). For the reduction related with the electrification of vehicles, the operational costs related with energy consumption will be reduced due to the better efficiency of the electric engine in comparison with the internal combustion engines (Badia & Jenelius, 2020a and 2020b).

One of the most potentially interesting aspects of the restructuration of the services with the arrival of the future mobility is the opportunity of combine the concept of ride-sharing with the changes in the vehicle technology in terms of propulsion technology (electrification) and the vehicle itself (automation) (Barceló Bugeda, Montero Mercadé, & Ros Roca, 2018) that will make the operation costs to be lower, as explained previously, making the ride-sharing services with autonomous electric vehicles competitive enough to substitute private cars (Burghout, Rigole, & Andreasson, 2015) or conventional buses (with their fixed routes and schedules) (Merlin, 2017).

While some studies about the implementation of autonomous vehicles carried out in different cities such as Lisbon (OECD/ITF, 2015), among others like Dublin, Auckland or Helsinki (also simulated by the International Transport Forum (ITF) of the OECD), and Oslo (PTV Group & COWI, 2019) have shown that is possible to slice the vehicle fleet to under 10% of the current fleet size.

All what has been described supposes a risk to conventional public transport, as the new automated vehicles introduced could substitute partly the service that public transport offers. However, this new technology could also improve the level of service supplied in public transport systems, making to work with smaller vehicles and higher frequencies possible (Zhang, Jenelius, & Badia, 2019a and 2019b). UITP advices that, depending on how the automated vehicles are regulated, it could lead to more cars on the road, more congestion and more urban sprawl (UITP, 2017) but it is also said that if they are putted in use as shared fleets they can reduce the number of cars and reaching places/people not reachable previously due to different reasons, strengthening a better service for first/last mile to feed the public transport main lines.

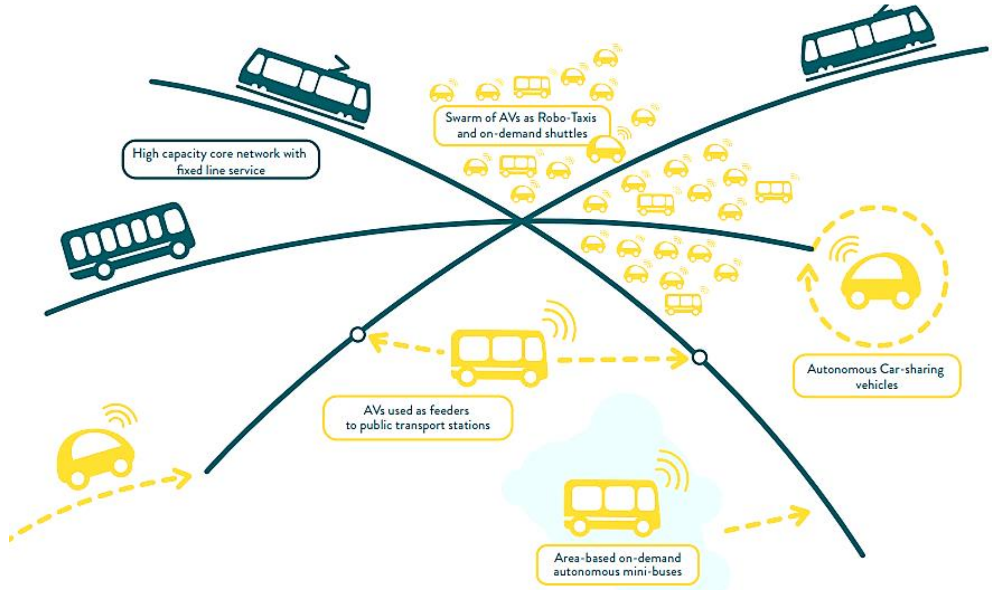


FIGURE 2. Possible applications of autonomous vehicles (AVs) as part of a diversified public transport system (UITP, 2017).

As shown in Figure 2, UITP holds that an integrated shared fleet of autonomous vehicles in combination with the traditional public transport network, is regulated and used properly, can lead to have a better urban future, with less noise and pollution, better efficiency of the traffic and more space for other uses different than parking.

In the same way (Shaheen & Chan, 2016) states that the gap in the transportation network between the first/last mile connectivity and the public transport transit can be potentially solved with the shared mobility, being it an alternative to the feeder bus services, normally costly. Only in combination with the conventional public transport, ride sharing systems lead to a sustainable offer in urban transport (PTV Group, 2019).

When comparing between the mentioned feeder services as a demand responsive transport or a fixed route one, it is necessary to use models or tools for doing it. The used tool in this document is the model developed by (Badia & Jenelius, 2020a and 2020b) which provides the costs of both services under certain circumstances and scenarios. The equations in which the tool is based are based on several contributions of several authors, detailed in the following paragraphs.

The initial contributions for feeder services modelling were focused on fixed route, as it is the traditional operating strategy and most common one. An optimization model for the bus spacing and headway that minimizes the total cost in a feeder system composed by parallel lines connecting a service area with a rail corridor was the contribution given by (Hurdle & Wirasinghe, 1980).

Additionally (Kuah & Perl, 1988) introduced the optimization of the spacing between the bus stops, obtaining robust results for modelling the optimization of fixed route feeder systems.

According to on-demand feeder systems (as many-to-one systems) it is remarkable the contribution of (Chang & Schonfeld, 1991) for comparing it with fixed route systems, identifying the optimal configuration through the minimization of the total cost, including the access, waiting, riding and time at stops and optimizing the vehicle size. The model gives which operation system is more competitive.

3. Stockholm urban planning and transport system

The public transport can be considered an accelerator of the urbanization since the nineteenth century, being the city of Stockholm continuously expanding itself and developing its public transport system to allow the developing of the city, mainly alongside the rail lines.

In this section the development of the city and its relationship with the development of the public transport network will be exposed. It is also presented the Stockholm's public transport system, to have a better understanding of the network.

3.1. Transit-oriented development in Stockholm

Water barriers around the islands and peninsulas that form the city and the narrow streets of the old inner city, made a necessity the construction of the metro system (*tunnelbana*) and the improvement of electrified commuter railroad lines (*pendeltåg*) to keep up the population increase in the mid nineteenth century (Joint Committee on Washington Metropolitan Problems, 1959).

These geographical configuration and urban characteristics made necessary to have a coordinated planning between the urban development and the rail transit, being one of the best examples of this kind of coordination anywhere (Cervero, 1995).

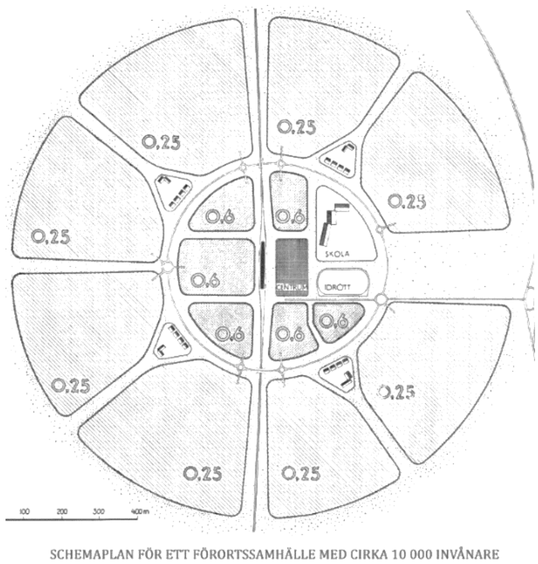


FIGURE 3. Schematic sketch for the ideal suburban community with about 10,000 inhabitants, as designed in *Framtida Stockholm,* the urban plan published in 1945 (Stojanovski, Lundström, & Haas, 2012).

The suburban areas were built with a certain pattern, based on the following elements:

- Service core or community centre containing the rapid transit station, office spaces for businesses and governmental agencies, commercial spaces and other facilities like churches or libraries.
- Inner belt of high-density housing, that generally extends around 500 meters from the train station being that an easy walking distance from the station

- Outer belt of low-density housing, that generally extends around 1000 meters from the train station
- Green belt to separate the different communities one from each other and from other land uses.

The mentioned station in the service core can be a local centre or a regional centre, serving a smaller or greater area respectively, being in both cases the commuter rail station a good point for the interchange of passenger between any of the different commuter train systems and feeder buses (Joint Committee on Washington Metropolitan Problems, 1959).

This pattern of urban suburbs in Stockholm is known as ABC suburb, where A stands for *arbete* (working), B for *bostad* (housing) and C for *centrum* (center), being this model the one applied during the urban development of the city during the twentieth century and which has shaped the city of Stockholm to what is known nowadays (Stojanovski, Lundström, & Haas, 2012).

This typology of suburban development would have never been possible without the development of a rapid transit railway system, such as the *pendetåg* or the *tunnelbana*, because thanks to it, it was possible to build residential areas further out of Stockholm's inner city on a larger scale (Stockholms stad, n.d.), but with an easy and quick access to the inner city thanks to the train systems.

The rail was a central element of the city design (Living Rail, n.d.) in the concept of the ABC suburbs that were planned and built in the mid nineteenth century, being Vällingby and Farsta the two more representative examples of it.

The urban development of the city continued unabated with the governmental Million Dwelling Programme, in which residential areas where constructed and, although the planification was not so accurate than with the ABC city model, each planned area sooner or later got its centre with commercial and service facilities but with few work places (Nilsson & Burch, 2006). Even with this, the new areas here always located alongside a rail transit line, being some examples of this type of developments Tensta, Hjulsta, Rinkeby or Bredäng.

As it can be observed, new urban developments, what have implied population growth, have been related with expansions or constructions of new public transport systems. It is corroborated with the relation between the population of the city and the expansion of its rail system, as it is shown in the following figure.

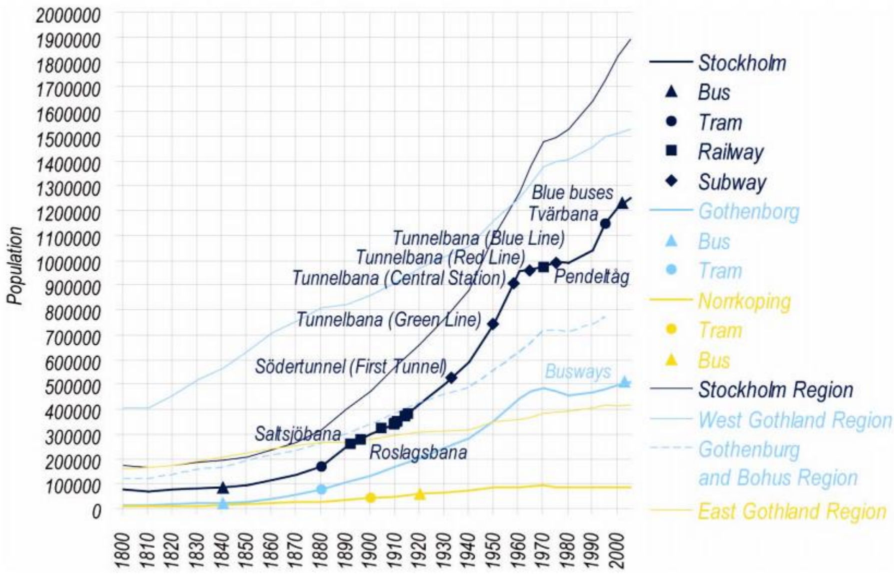


FIGURE 4. Population growth in different cities in Sweden (Stockholm, Gothenburg and Norrkoping) and the expansion of its public transport systems (Stojanovski, Lundström, & Haas, 2012)

This model has made Stockholm one of the most successful transit-oriented development (TODs) cities, as the centres of the mentioned ABC suburbs acts as public transport nodes, balancing the public transport demand between the different suburbs, acting as satellites (Stojanovski, Lundström, & Haas, 2012).

3.2. Public transport system

The importance of the transport system design in the Stockholm development has been addressed, being Stockholm is one of the most successful TODs cities. The characterization of the Stockholm's public transport system is important to contextualize the following sections of this document.

The Stockholm's public transport system operates in the Stockholm Country, being SL (Storstockholms Lokaltrafik, n.d.) the organizer of the services.

The public transport system consists of bus, *Tunnelbana* (metro), *Pendetåg* (rail), *Lokalbana* (light rail), *Sparvågn* (tram) and ferry and around 3 million travels are carried out every day (on a normal winter day) (AB Storstockholms Lokaltrafik, 2018).

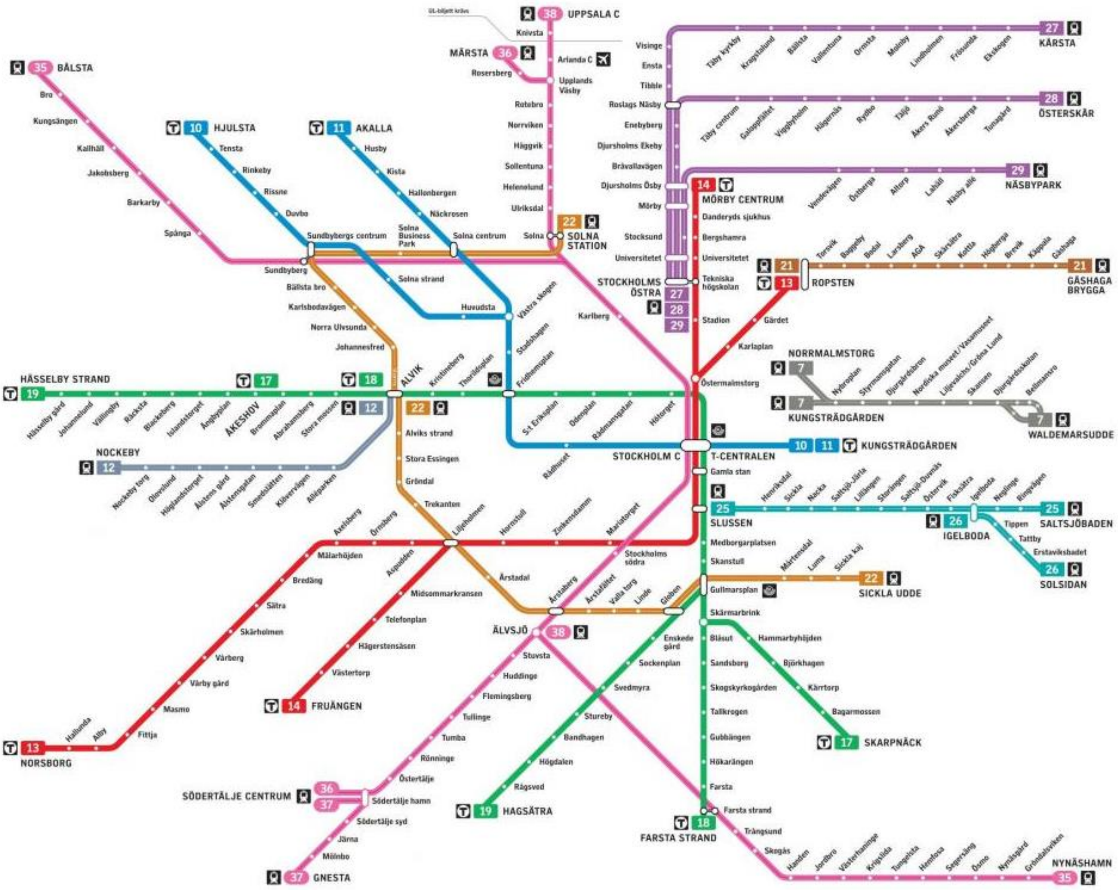


FIGURE 5. Rail network in the SL system within the Stockholm county
[Source: Stockholms Lokaltrafik SL, https://sl.se/]

3.2.1. Bus

In total, there are 488 bus lines with 6584 stops in its 9026 km within the Stockholm County. The bus lines are classified between the ones that operates in the inner city and the ones that operates in the suburbs. Some other services like the night buses and service/local lines exists, being them mentioned later.

3.2.2. Tunnelbana

It consists of 7 lines that are formed by several branches and classified by colours (red, blue, and green). The network has a total of 108 km, with 100 stations. The lines are shown in the following table.

TABLE 2. Metro lines in the Stocholm's public transport network

line		stretch
10	blue line	Kungsträdgården - Hjulsta
11	blue line	Kungsträdgården - Akalla
13	red line	Norsborg - Ropsten
14	red line	Fruängen - Mörby centrum
17	green line	Åkeshov - Skarpnäck
18	green line	Vällingby - Farsta strand
19	green line	Hässelby strand - Hagsätra

The headway in the metro lines in working days during most of the day (from 6am to 21pm) is 10 minutes, being the headway greater during weekends or for the night traffic.

According to the metro, there are plans to extend it, as shown in Figure 6 in combination with the existing lines.

FIGURE 6. Tunnelbana map, with the future expansions planned
[Source: Nya Tunnelbanan https://nyatunnelbanan.sll.se/]

3.2.3. Pendetåg

The regional/suburban rail connects the inner city of Stockholm with different places outside the city within the county. The network has a length of 241 km with a total of 53 stations. The lines that composes this network are:

TABLE 3. Regional/suburban rail lines in the Stocholm's public transport network

line	stretch
40	Uppsala - Arlanda C - Stockholm City - Södertälje centrum
41	Märsta - Stockholm City - Södertälje centrum
42X	Märsta - Stockholm City - Västerhaninge - Nynäshamn
43	Bålsta - Kungsängen - Stockholm City - Västerhaninge - Nynäshamn
43X	Kallhäll - Stockholm City - Västerhaninge - Nynäshamn
44	Kallhäll - Tumba
48	Stockholm City - Södertälje centrum - Gnesta

In Figure 5 the pendetåg lines are shown with the rest of rail network in the SL system.

3.2.4. Lokalbana

There are five lines of light rail divided in two different networks that are separated from the rest of rail network of the public transport system. The two different networks referred are Roslagsbanan (3 lines from the inner city towards the north), with a length of 65km and 38 stations, and Saltsjöbanan (2 lines from the inner city towards the east), with 17 km and 18 stations.

TABLE 4. Light rail lines in the Stocholm's public transport network

line		stretch
25	Saltsjöbanan	Slussen– Saltsjöbaden
26	Saltsjöbanan	Igelboda – Solsidan
27	Roslagsbanan	Stockholms östra– Kårsta
28	Roslagsbanan	Stockholms östra– Österskär
29	Roslagsbanan	Stockholms östra– Näsbypark

In Figure 5 the lokalbana lines are shown with the rest of rail network in the SL system.

3.2.5. Sparvågn

There are four tram lines, located in Lidingö (Lidingöbanan) and the city of Stockholm (Spårväg City, Tvärbanan and Nockeybanan). Each one of the tram lines mentioned are not connected with each other, as they are located across different places in the city. The total length of all the tram lines is 38km, with 61 stops in total.

TABLE 5. Tram lines in the Stocholm's public transport network

line		stretch
7	Spårväg City	Sergels Torg - Waldemarsudde
12	Nockebybanan	Nockeby - Alvik
21	Lidingöbanan	Ropsten - Gåshaga brygga
22	Tvärbanan	Sickla - Alvik - Solna Station

In Figure 5 the tram lines are shown with the rest of rail network in the SL system.

3.3. Experiences related to DRT in Stockholm

Two experiences related with demand responsive transport services can be mentioned in the Stockholm county with interest to the purpose of this project, one totally implemented (but with no relation with automation of the vehicles or electrification) and one in the process of being fully implemented by 2025 (and with automation and electrification).

3.3.1. Närtrafik in residential areas

The service bus (being *Närtrafik* the commercial name used by SL) is an alternative to the traditional travel services, specially designed and adapted for old (and that mostly runs in areas with a big percentage of elderly people living) or disabled people, and which objective is to help these people to get to local services or facilities (Storstockholms Lokaltrafik, n.d.).

There are two types of operation system for this service, the scheduled services (*linjetrafiken*) and the ordering services (*beställningstrafik*). The first one operates as a traditional service of bus, with a schedule and fixed stops. The second type, the ordering service, is a local type of service that works without stops as they are traditionally conceived but that works with meeting places or even arriving to the desired destination if it is possible. The bus size varies between two types, smaller buses with 5 seats and a wheelchair space or bigger buses, with around 15-20 seats. The adaptation of this type of services specifically for the elderly and disables is evident with the fact that the smaller buses has the floor on the same level than the sidewalk.

The areas where the buses can be ordered are just a few and they respond to certain social reasons to have it implanted. The areas where it is possible to use *beställningstrafik,* which are booked through a phone call, are Årsta, Spånga, Hagsätra, Rågsved, Högdalen, certain parts of Bandhagen, Danderyd, Bromma, Vällingby, Haninge and Nynäshamn.

FIGURE 7. Närtrafik line 968 around Lillbrostigen - Alceahuset – Slussbrostigen
[Source: Svenska Omnibusföreningen, https://forum.omnibuss.se/index.php?topic=56865.0]

3.3.2. Automated buses in Barkaby

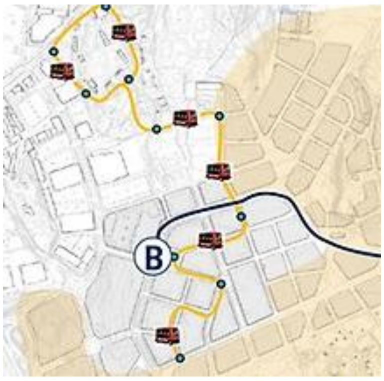
Currently a project to implement self-driving buses (*självkörande bussar*) is carried out in the Barkaby area, which has meant to have the first line in the world with self-driving regular scheduled buses. The agreement between the operator (Nobina), municipality (Järfälla) and the Stockholm County Council, owner of SL, wants to get the world's most modern city traffic, that will arrive early and grows in line with the new urban development of Barkabystaden. Some of the aims of the project during the investment timespan are (Barkarbystaden, n.d.):

- To get the Europe's first self-driving electric buses in regular scheduled traffic that will be able to pick up the passenger outside the door at home for transport door to door.
- To get high-capacity, electric-powered high-speed buses with infrastructure according to the BRT standard
- Electrification of other bus traffic for a modern, quiet, and emission-free public transport.

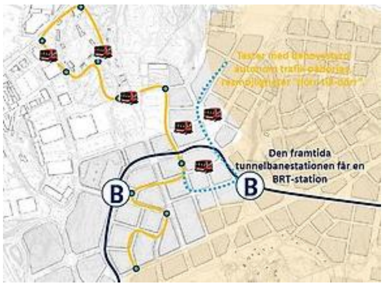
The project is composed of several stages (Barkarbystaden, n.d.), that are described below.

Stage 1 (around fall of 2018), pilot traffic in the line 549 with three self-driving (but always with a host on board) minibuses (up to 12 people) in the newly built neighbourhoods in Barkabystaden, with possibility to change to conventional bus lines and with speeds around 15km/h.

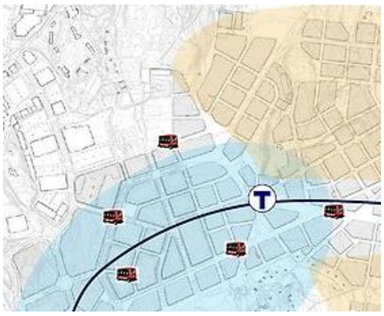
Stage 2 (around spring of 2019), evaluation of the pilot with possibility to expand it in length of the line and/or number of vehicles.



Stage 3 (during 2020), inauguration of the BRT line (the line will act as a first step towards the subway and offer similar qualities in the journey between Barkarbystaden and Akalla with high frequency, stable traffic, fast boarding, fast journeys with half the travel time today). The operation of the self-driving vehicles in the 549 line is not changed in this stage.



Stage 4 (in 2021), extension of the BRT to Barkaby station and increase of the number of vehicles. Tests starts for the on-demand self-driving minibuses, providing a door to door service, with public transport arriving closer and through every street in the Barkabystaden



Stage 5 (in 2025), with inauguration of the blue metro line until Barkaby station (with a station in Barkabystaden) and after the test period carried out in the stage 4, the initial aim of the project is to achieve a public transport in which the on-demand self-driving minibuses are able to work in all the area of the Barkabystaden, being possible to have a service with no fixed stops nor lines and that can get the passengers from the door of their origin/destination to the metro station.

The current situation is the stage 2, in which the line 549 is operating as any other SL line (fixed schedule and fixed stops) but with self-driving and the construction of the infrastructure for the implementation of the BRT is being carried out. In the information found in Figure 8, it can be seen that the line is operated by autonomous (self-driving) buses (*Linjen trafikeras med autonoma (självkörande) bussar)*

549 **Kaptensvägen–Flygfältsvägen**

Giltighetstid	Övrig information	Observera!
17 februari–18 juni 2020	Linjen trafikeras med autonoma (självkörande) bussar.	Linjen går ej 11/4 och 30/4.

549	Måndag–fredag	Var 15:e minut				
Kaptensvägen	06.31	46	01	16	31	18.31
Löjtnantsvägen	06.34	49	04	19	34	18.34
Stora torget	06.37	52	07	22	37	18.37
Lansengatan	06.39	54	09	24	39	18.39
Flygfältsvägen	06.41	56	11	26	41	18.41

FIGURE 8. Winter schedule and stops for the line 549
[Source: Storstockholms Lokaltrafik, https://sl.se/ficktid/vinter/v549b.pdf]

FIGURE 9. Self-driving vehicles used in the line 549.
[Source: Mitti Järfälla, https://mitti.se/nyheter/vinnova-bussarna-barkarbystaden/?omrade=jarfalla]

4. Suitability to implement DRT

In the actual situation, flexible public transport systems are operated just in a few places due to its high costs, being most of them operated in places with low or very low-density populations, mainly rural areas.

Even with it, in larger urban areas, such as Stockholm, there are certain circumstances in which flexible public transportation can be operated. These considered circumstances in which is possible to implement a flexible service are, e.g., feeding a fixed-route of major transit line, such as metro or commuter lines, feeding a major traffic generator, serving to areas with low-density or serving at time with low demand, as it can be night-time (Transportation Research Board, 2010).

As it is also mentioned in (Denver Regional Transit District (RTD), 2008), major transportation activity centres, such as rail stations and transit hubs, located in low-density urban areas are propitious to implement flexible public transportation services, as research has shown.

4.1. Susceptibility-related variables

Travel behaviour is influenced by land use and its determinants, as it can be the density, mixed land use, neighbourhood design, and distance of origins and destinations to public transport nodes (Wee, 2013). Some of the mentioned aspects included in the land use variables constitute the urban configuration and access to transit, which requires special attention when analysing the susceptibility to implement DRT services.

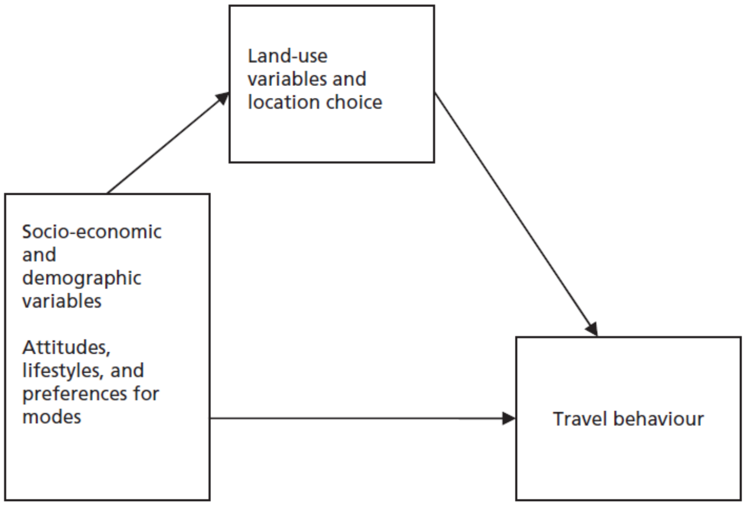


FIGURE 10. Current approach of the relation between the land-use, socioeconomic and demographic variables and attitudes with the travel behaviour (Wee, 2013)

The susceptibility to implement flexible services, as a new behaviour when travelling will be analysed in two different perspectives:

- Analysing the variables related with socioeconomics and demographics
- Analysing the variables related with urban configuration and access to transit

With the analysis of the different variables, a criterion for identifying which zones are suitable to have a flexible service implemented will be created. With the criterion, a characterization of Stockholm will be performed for the purpose of achieving a clear classification of where the study will be conducted.

4.1.1. Socio-economic and demographic variables

As it was mentioned before, socio-economic, and demographic variables play a key factor in travel behaviour. Although demographic data from the census is the most commonly used data source for service area characteristics, there are several indicators when planning public transportation services (Mistretta, Goodwill, Gregg, & DeAnnuntis, 2009). The mentioned document lists them into several categories, such as population density, employment density, age, income, and vehicle availability.

Several studies about the parameters favourable to use DRT show those effects. DRT services demand is higher in areas with low population density and with high levels of social deprivation, being it measured with statistical data about medium income, employment or education (Wang, Quddus, Enoch, Ryley, & Davison, 2014). DRT riders are typically those who are likely to be poor (with lower medium income), elderly and disadvantaged (Spielberg & Pratt, 2004).

The performance of flexible public transportation is highly related with five socio-economic and demographic variables, with the highest correlation between them, as it is mentioned in (Transportation Research Board, 2010). These variables are population density, employment density, senior density, youth density and medium income.

Although it is not one of the most correlated variables, the literature review has derived, with several mentions to it, the importance of the car ownership to the demand for DRT services.

The table 6 shows how the mentioned factors will affect the susceptibility to use DRT, according to the six socio-economic and demographic variables listed.

TABLE 6. Relation of socio-economic and demographic parameters influencing the DRT demand

factors	**demand for DRT services**
senior density	directly related
youth density	directly related
population density	inversely related
employment density	inversely related
medium income	inversely related
car ownership	inversely related

The source of the values of the different factors mentioned is the *DeSO - Demografiska statistikområden,* as it will be described in detail later in the procedure and criterion determination section.

4.1.2. Urban configuration and access to transit

Passengers using public transportation generally assume certain distances to access it, with different values depending on the mode. In all the cases the transit use by walk access decrease as walking distance increases.

- For bus stops, the common limit used as walking distance assumed by the passengers to access the bus route is 400m (Tal, Handy, & Boarnet, 2013) (O'Neill, Ramsey, & Chou, 1992).
- For train stations, the upper limit for calculating the service population and transit service catchment is suggested by several studies to be 800m (Agrawal, Schlossberg, & Irvin, 2008) (Zhao, Chow, Li, Gan, & Ubaka, 2003) (Transportation Research Board, 2003), although

some of them rank that upper limit between 800 and 1600m, corresponding it to a distance between 0.5 and 1 mile.

As it has been shown, walking distances to access the transit lines is a key factor, but not the only one. Research about potential in increasing rail use shown that improving the quality of the access facilities to the railway stations is likely to increase the rail use, especially with infrequent rail passengers (Brons, Givoni, & Rietveld, 2009). From the mentioned research it is also remarkable as a conclusion that improving the public transportation services to the station is a crucial factor when deciding how to improve the access to the stations.

The quality of the access to the transit station varies between the different locations of them, being a possible solution to improve it the implementation of DRT services. To distinct the areas in which the access to the transit station is poor, and it would be desirable to implement DRT to improve it, the procedure described in the next sub-section is carried out.

4.2. Procedure and criterion determination

The criterion to determine the areas suitable to implement DRT is based in the related aspects to urban configuration and access to transit, reducing the number of zones considerably from the total number of zones existing in the Stockholm county. Once this first step is done, the factors described in Table 6 are calculated for each one of the zones, to have a selection based not just in urban configuration and access to transit, but also in the demographic and socioeconomic variables, parameters that altogether influence the travel behaviour.

For it, the information described below has been used.

- Geographical information
    - Base area map of the Stockholm county following the division of the *Regionala utvecklingsplan för Stockholmsregionen - RUFS* (Regional Development Plan for the Stockholm Region), specifically the division, names and codes given in the *Basområdeskartor 2010* (Region Stockholm. Tillväxt- och regionplaneförvaltningen, n.d.). This information has been provided by the Transport Planning department of the KTH.
    - Base area map of Sweden, following the division of the *Statistiska centralbyrån (SCB)*, specifically the *DeSO - Demografiska statistikområden* (demographic statistics areas) (Statistiska centralbyrån, n.d.). DeSO areas are an open source geodata, with nationwide division that follows the county and municipal boundaries and has available statistics of population (e.g. by age, sex, background, employment, or education level), household and vehicle information.
    - Urban agglomeration information, provided by the *Statistiska centralbyrån (SCB)* (Statistiska centralbyrån, n.d.), having available the boundaries for urban areas with at least 200 inhabitants and being it displayed as polygons.
- Public transport supply information
    - GTFS Regional static data for SL containing files with the planned public transport in the Stockholm county. The General Transit Feed Specification (GTFS) is a data specification that allows public transit agencies to publish their transit data in a format that can be consumed by a wide variety of software applications (GTFS, n.d.). The information is available via APIs in the Trafiklab webpage (Trafiklab, n.d.). Although the information is still named as beta, it is trustable, and it will be soon fully stable. The information provided by the API contains:
        - Agency
        - Calendar
        - Calendar dates

    - Feed information
    - Routes
    - Shapes
    - Stop times
    - Stops
    - Transfers
    - Trips
- Public transport demand information
    - Demand matrices for the RUFS zones for all the Stockholm county, both for a complete day (00:00 to 24:00) and for the peak hour (07:00 to 08:00). This information has been provided by the Transport Planning department of the KTH. The information contained in the demand matrix is the number of travels between zones.

The steps considered that will be detailed in this section are:

1. Processing of the input public transport supply
2. Definition of zones with a poor first/last mile service
3. Restriction to urban agglomerations
4. Elimination of non-valid areas
5. Aggregation of zones to obtain DRT suitable areas
6. Obtention of parameters to characterize the zones

4.2.1. Processing of the input public transport supply

The first step has been processing the input public transport supply information with the database management system Microsoft Access due to the size of the information contained in the files and in order to have relations between the different attributes contained in the files with the purpose of obtaining a headway for each stop of the public transport system.

The study aims to be performed in hours with a regular supply of public transport and for that, it is just considered working days and excluding certain hours during the day, coincident with night-time. According to the temporal distribution of passengers boarding in all the services available in SL, the 93% of these travels are done between 06:00 and 21:00 (daytime) while just the 7% are done between 21:00 and 6:00 (AB Storstockholms Lokaltrafik, 2018). This can be seen in the following figure:

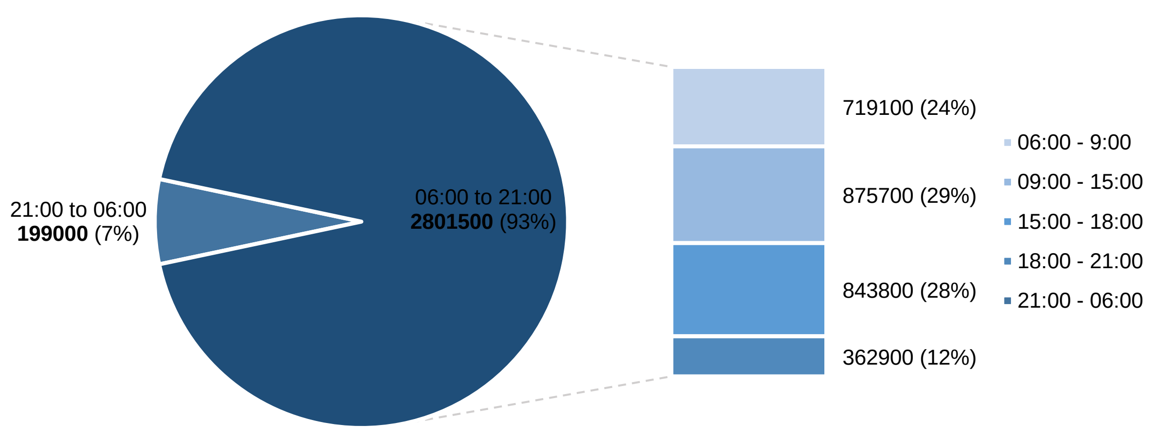


FIGURE 11. Temporal distribution of the number of passengers boarding in the SL network, with data from (AB Storstockholms Lokaltrafik, 2018)

The conditions imposed in the filters for it, are:

- Filter the calendar dates file to select one working day, excluding any other information apart from it. The selected date is Wednesday 4th of March of this year (2020), considered a good day as it is not a weekend day or a vacation day.
- Filter the stop times file to select daytime, considered from 6:00 to 21:00 (15 hours), when the services are more regular and has a smaller headway.

The headway for each stop is calculated with the division of the total daytime considered, 15 hours, by the sum of arrivals to each stop.

The output is a .csv file containing information about stops (name, ID, latitude, longitude, and headway).

TABLE 7. Input, procedure, and output for the step 1

input	**procedure**	**output**
Text files (.txt) from GTFS Regional static data.	Filter the calendar dates file to a selected working day. Filter the stop times file to select daytime.	Text file (.csv) containing information about stops.

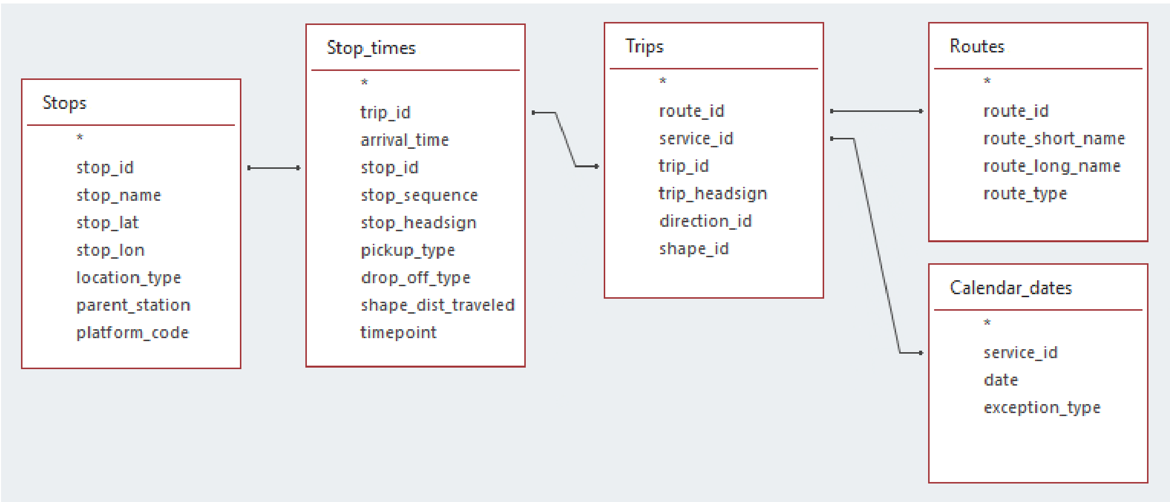


FIGURE 12. Relations between the different documents and fields contained in the GTFS regional static data for SL introduced in Microsoft Access.

4.2.2. Definition of zones with a poor first/last mile service

In order to define the areas in which the first/last mile service is poor, and DRT would be suitable to be implemented, the conditions mentioned below has been considered.

- Being between 800 m and 2000 m to a tunnelbana, lokalbana or pendetåg station, considering that almost all these stations have a headway lower than 10 minutes. Passengers with the origin or destination in a radius smaller than 800 meters to a train station are assumed to access them by feet, as it is considered as limit used as walking distance to a train station, as mentioned in section 4.1.2. The analysis is for first/last mile solutions, so the upper limit for the possible DRT service implementation has been extended until 2000 meters, slightly greater than 1 mile.

- Being not closer than 400 m to a bus stop with a headway lower than 10 minutes. That distance is considered because the common limit used as walking distance assumed by the passengers to access the bus route is 400m, as it was mentioned in previous sections.

Buffers for train stations have been created for distances of 800 and 2000 meters and a buffer of 400 meters for bus stops with a headway lower than 10 minutes. The deference algorithm in QGIS is processed to eliminate from the 2000 meters buffer the areas of the 800 meters buffer and the 400 meters buffer of the bus stops, obtaining results like the ones appearing in Figure 13.

TABLE 8. Input, procedure, and output for the step 2

input	procedure	output
text file (.csv) containing information about stops shape file (.shp) containing the base area map of the Stockholm county (RUFS)	buffering to bus stops with low headways and to train stations difference of the buffers clip the difference layer with respect to the base area map	shape file (.shp) containing zones with a poor first/last mile service

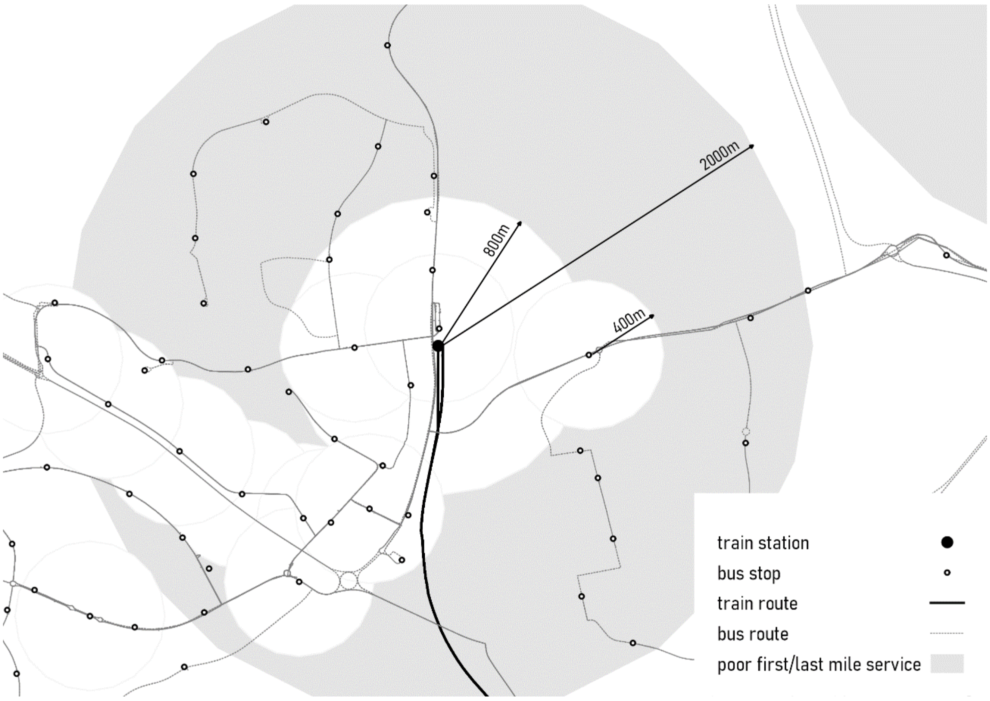


FIGURE 13. Example definition in QGIS of the poor first/last mile service.

The difference layer has been clipped with respect to the base area map of the zones in the Stockholm county, obtaining 639 zones, as shown in the following figure.

FIGURE 14. Example definition in QGIS of the poor first/last mile service clipped zones.

4.2.3. Restriction to urban agglomerations

Although in the previous step the water bodies are not included, some of the resulting clipped zones may are not part of an urban agglomeration, what would not be viable for the implementation of first/last mile services. In order to obtain urban zones, the difference with the urban agglomeration layer from the SCB mentioned above has been performed. A total of 593 zones are obtained.

FIGURE 15. Example definition in QGIS of the zones with poor first/last mile service within an urban agglomeration area.

TABLE 9. Input, procedure, and output for the step 3.

input	procedure	output
Shape file (.shp) containing zones with a poor first/last mile service Shape file (.shp) containing urban agglomeration information	Difference of both layers	Shape file (.shp) containing zones with a poor first/last mile service within an urban agglomeration area

4.2.4. Elimination of non-valid areas

With a total number of 593 zones and with a brief analysis of them, the need of some filter to eliminate non-valid resulting zones is obvious. Zones in which the suitability to implement DRT has an area lower than the 30% of the total area of the zone are considered negligible, as they create small isolated zones or areas too small to consider the implementation of the service. With this filtration, the number of zones gets reduced to 187.

The resulting 187 zones with satellite images, are classified in the following categories:

1. Residential area. Being the zones in this group the selected zones. The total number of zones containing this group is 79.
2. Industrial area. Not considered because of the lack of information of some parameters that take part in the analytical analysis, such as the household medium income. The analysis of implementation of DRT in industrial areas can be included in future studies.
3. Natural (park/forest) area. Not considered because the service is intended to serve to residential areas.
4. Out of reach area. Not included because there are barriers between the train station which the DRT would be linked to and the area, such as water bodies or lack of a road communication.

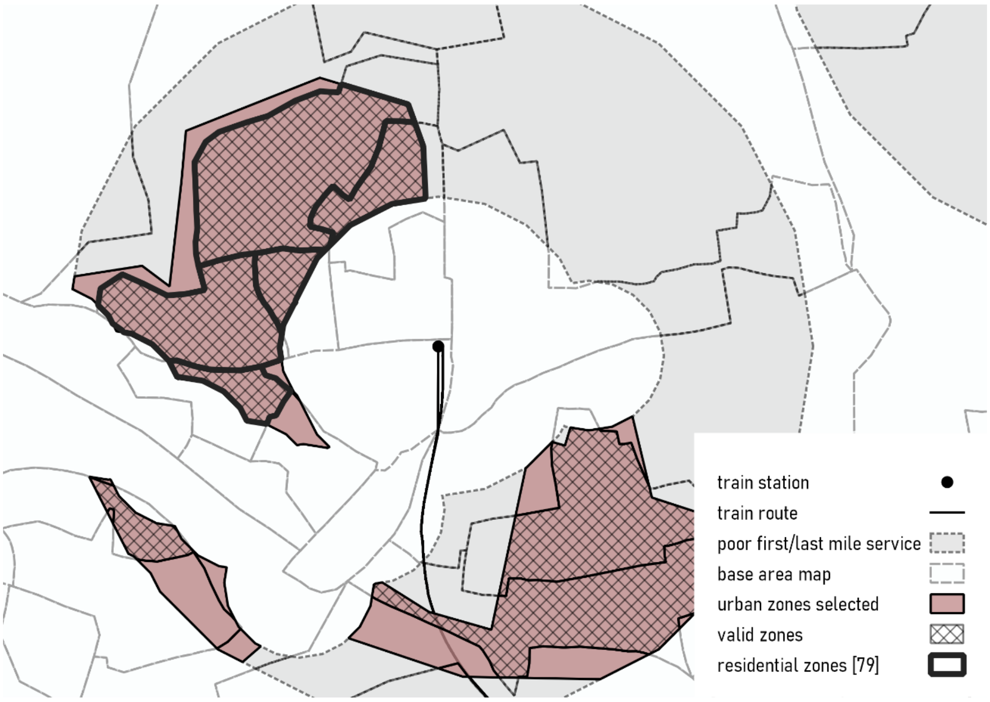


FIGURE 16. Example definition in QGIS of the residential zones with poor first/last mile service within an urban agglomeration area.

TABLE 10. Input, procedure, and output for the step 4.

input	procedure	output
Shape file (.shp) containing zones with a poor first/last mile service within an urban agglomeration area	Elimination of areas in which the selected area is lower than 30% of the area of its respective RUFS zone Elimination of isolated areas Elimination of zones that are not residential or are not compatible with the service	Shape file (.shp) containing residential zones with a poor first/last mile service within an urban agglomeration area

4.2.5. Aggregation of zones to obtain DRT suitable areas

With the obtention of residential zones with a poor first/last mile service within an urban agglomeration area, an aggregation of these zones according to the train station which would serve the DRT service is performed, with the obtention of 34 areas suitable to have the DRT service implemented.

TABLE 11. Input, procedure, and output for the step 5.

input	procedure	output
Shape file (.shp) containing residential zones with a poor first/last mile service within an urban agglomeration area Shape file (.shp) containing information about stops	Aggrupation of the zones according to the closest train station for implementing first/last mile service	Shape file (.shp) containing areas suitable to implement DRT service

FIGURE 17. Example definition in QGIS of the DRT suitable areas

4.2.6. Obtention of parameters to characterize the zones

Once the limits of the 34 areas suitable to implement the DRT service is defined, the values of important characteristics for the analysis must be calculated, being the hourly demand density and the household medium income two of those parameters that will directly influence the results of the analytical model. Besides, the rest of the socioeconomic and demographic parameters listed in Table 6 are also calculated in this step.

The hourly demand density is included in the RUFS base area map of the Stockholm county. Initially, this information was provided as an OD matrix with the number of travels, but for the obtention of the demand density per each zone, the sum of rows and columns has been performed, being possible to obtain the total number of travels from and to each RUFS zone. With the total number of travels, the area of each RUFS zone and the time interval for which the matrix was referred (peak or a whole day), the hourly demand density is obtained.

TABLE 12. Input, procedure, and output to obtain the hourly demand density attribute.

input	procedure	output
Shape file (.shp) containing the base area map of the Stockholm county (RUFS) Demand matrices (in .txt) for the RUFS zones Shape file (.shp) containing areas suitable to implement DRT service	Sum of demand from/to each RUFS zone Rasterization of the RUFS layer for the demand density field Use of zonal statistics to add the medium values of the raster layers in the suitable areas	Shape file (.shp) containing areas suitable to implement DRT service including a demand density attribute

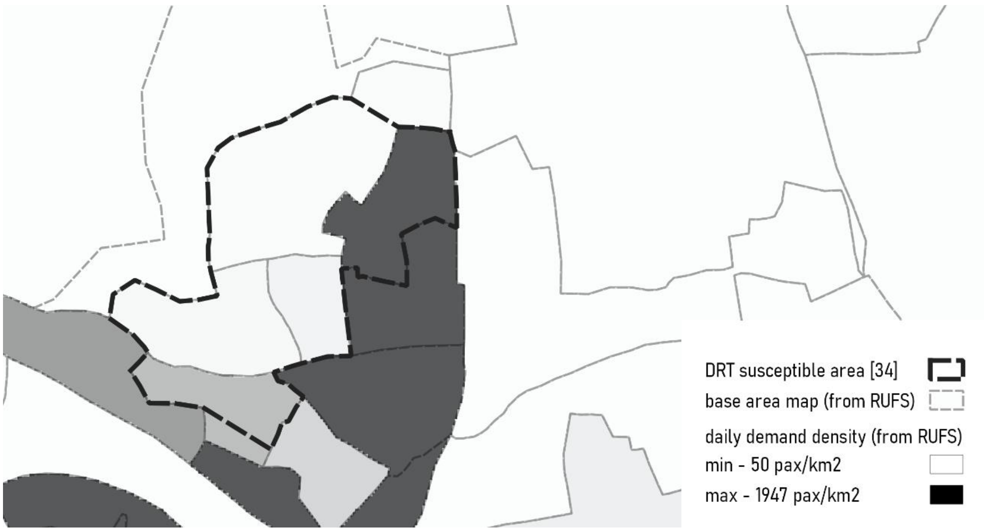


FIGURE 18. Example of the rasterization in QGIS of the RUFS layer for the hourly demand density field

The household medium income is included in the DeSO base area map of the Stockholm county and with the rasterization and use of zonal statistics its obtention is direct. The information contained in the DeSO base area map contains more fields that can be extracted in the same way if a more accurate socio-economic analysis is required.

TABLE 13. Input, procedure, and output to obtain the household medium income attribute

input	procedure	output
Shape file (.shp) containing the base area map of the Stockholm county (DeSO) Shape file (.shp) containing areas suitable to implement DRT service	Rasterization of the DeSO layer for the medium income field Use of zonal statistics to add the medium values of the raster layers in the scope the areas suitable to implement DRT service	Shape file (.shp) containing areas suitable to implement DRT service including medium income attribute

FIGURE 19. Example of the rasterization in QGIS of the DeSO layer for the household medium income field

With the purpose of evaluate the suitability to implement DRT not only on urban configuration and access to transit parameters but also on socioeconomic and demographic parameters, the calculation and extraction of information about additional parameters to the household medium income and the hourly demand density is performed.

The parameters also calculated in this step are the ones listed in Table 6, senior density, youth density, population density, employment density, and car ownership, and the methodology to evaluate them is the same that the one followed for the household medium income, shown in Table 13 and figure 19.

4.3. Results

With the steps described in the previous section, 34 areas with suitability to implement DRT according to the urban configuration and access to transit are chosen to perform the analysis. Not just the urban configuration and access to transit are factors dependent of the success for the implementation of DRT and more characteristics of the areas must be considered.

In the following table all the areas are listed, with information about household medium income and hourly demand density, among others. The values of the demand density shown correspond to the consideration that most of the travels are between 06:00 and 21:00 (15 hours) and the obtention of the hourly demand density is through the division of the daily demand density between the demand period of 15 hours.

TABLE 14. Selected areas with suitability to implement DRT with its characterization

id	zone name	hourly demand density *(pax/km^2-h)*	senior popilation rate	youth population rate	population density *(people/km^2)*	household medium income *(SEK/year)*	unemployment rate	car ownership *(car/household)*
1	Ensta - Ella	75.52	0.16	0.32	1625.99	424797.84	0.13	1.29
2	Viggbyholm	50.10	0.14	0.32	677.53	461961.60	0.14	1.36
3	Huddinge - Solgård	77.09	0.11	0.26	1465.79	369895.30	0.12	0.92
4	Södra Djursholm	66.15	0.24	0.30	1104.92	391891.97	0.28	1.32
5	Vega - Norrby	6.76	0.08	0.33	321.85	369909.63	0.12	1.24
6	Vega - Söderby	77.48	0.15	0.31	1804.09	352643.71	0.11	1.09
7	Långsjö	162.24	0.11	0.34	2928.68	437903.05	0.11	1.04
8	Herrängen	130.65	0.12	0.35	2657.41	441068.43	0.12	1.12
9	Havsörnstorget	92.04	0.10	0.28	3422.48	254020.42	0.28	0.66
10	Ormbacka - Skälby gård	89.37	0.09	0.36	1827.24	385952.28	0.12	1.24
11	Jakobsberg - Berghem	94.40	0.14	0.30	1079.30	355598.29	0.14	1.16
12	Helenelund	106.53	0.14	0.33	2047.72	440744.65	0.14	1.08
13	Nora - Klingsta	102.36	0.13	0.31	1672.74	448139.57	0.16	1.09
14	Stocksund	76.73	0.15	0.33	1221.99	419824.98	0.21	1.08
15	Ellagård	95.22	0.17	0.31	1768.25	422831.05	0.13	1.18
16	Kallhäll	108.72	0.16	0.27	1768.45	323412.85	0.17	0.98
17	Hässelby	123.58	0.15	0.31	2343.16	387274.69	0.14	1.15
18	Sundby - Flysta	130.15	0.12	0.29	2333.16	371326.61	0.15	1.02
19	Nälsta	182.19	0.15	0.31	3560.60	360806.55	0.16	1.04
20	Märsta	107.98	0.17	0.25	2067.93	293981.59	0.18	0.93
21	Fågelsången - Skansen	117.31	0.15	0.31	2318.45	420682.54	0.15	1.08
22	Töjnan	99.26	0.16	0.30	1858.01	381507.12	0.14	1.20
23	Kungsängen	92.70	0.16	0.26	1055.89	305791.31	0.18	0.89
24	Bro	64.39	0.13	0.31	2196.05	296806.94	0.20	1.03
25	Tumba	117.56	0.14	0.28	1882.16	291816.89	0.21	1.03
26	Tullinge	91.38	0.13	0.30	1895.21	359871.38	0.13	1.06
27	Huddinge - Kynäs	63.96	0.15	0.30	1828.50	368084.23	0.12	1.19
28	Huddinge - Vistaberg	65.95	0.08	0.37	1815.01	421333.49	0.10	1.16
29	Trångsund	61.36	0.12	0.31	1509.60	385428.14	0.13	1.04
30	Rönninge - Salems	117.51	0.19	0.28	2971.57	304002.33	0.18	0.93
31	Rönninge - Uttringe	27.48	0.15	0.31	406.57	406478.69	0.10	1.24
32	Södertälje	248.63	0.15	0.24	4310.61	274148.12	0.23	0.75
33	Ängby - Bromma	139.47	0.12	0.34	2447.61	448262.37	0.14	1.02
34	Råcksta - Beckomberga	217.22	0.14	0.28	4913.27	351767.82	0.17	0.71

In Figures 20 to 25 the location of the different areas is shown, both for the south and north from the inner city of Stockholm. In these figures the household medium income and the hourly demand density is depicted, two variables that are directly influencing the values obtained in the analytical model.

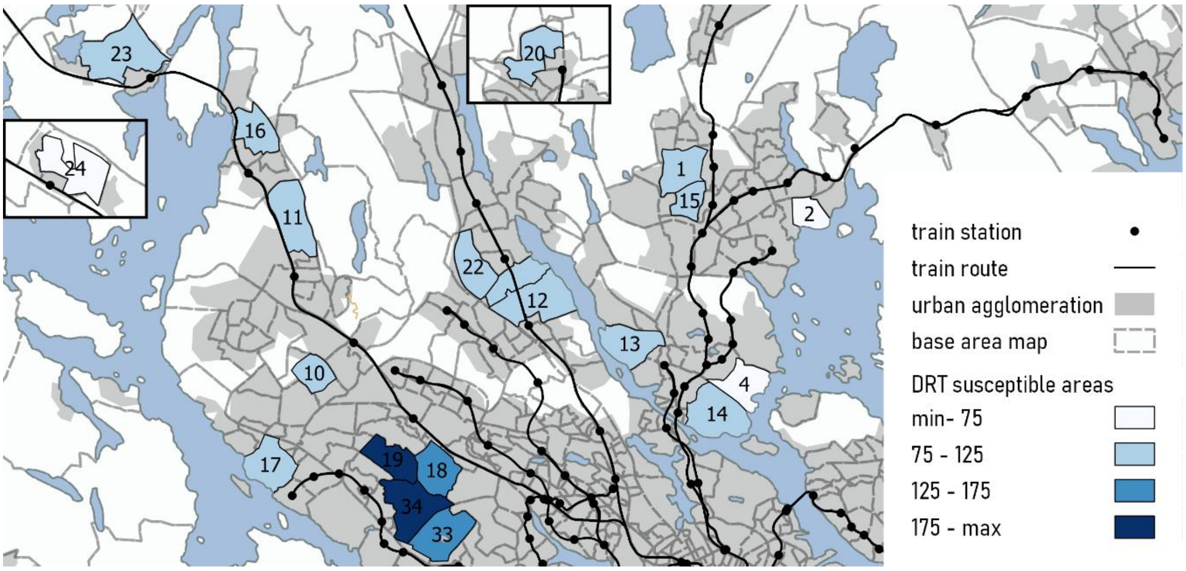


FIGURE 20. Location of the suitable areas to implement DRT in the north of the inner city, with hourly demand density (in pax/km^2-h)

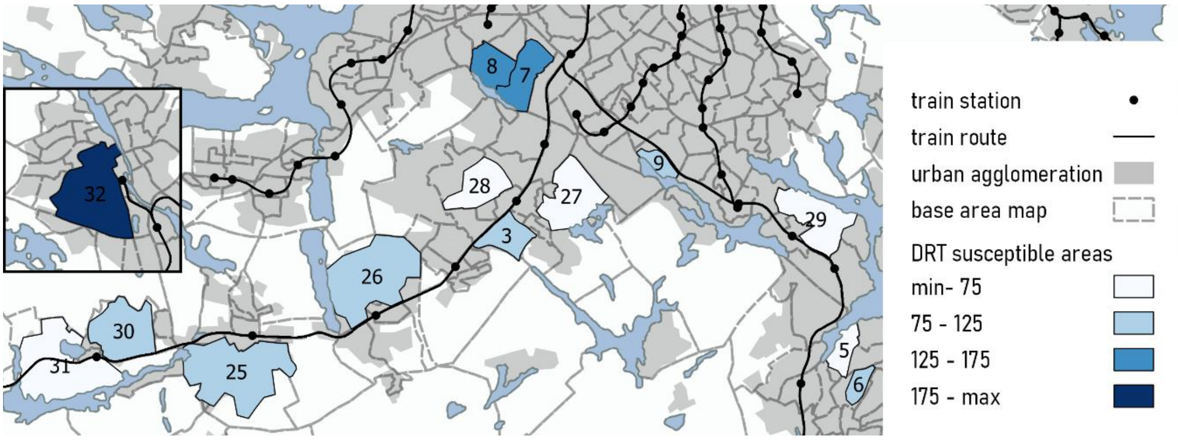


FIGURE 21. Location of the suitable areas to implement DRT in the south of the inner city, with hourly demand density (in pax/km^2-h)

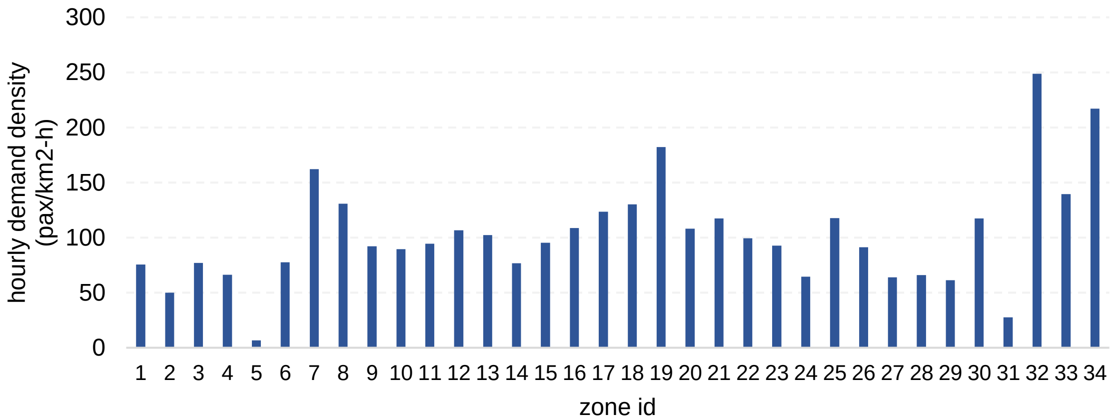


FIGURE 22. Hourly demand density for each area suitable to implement DRT

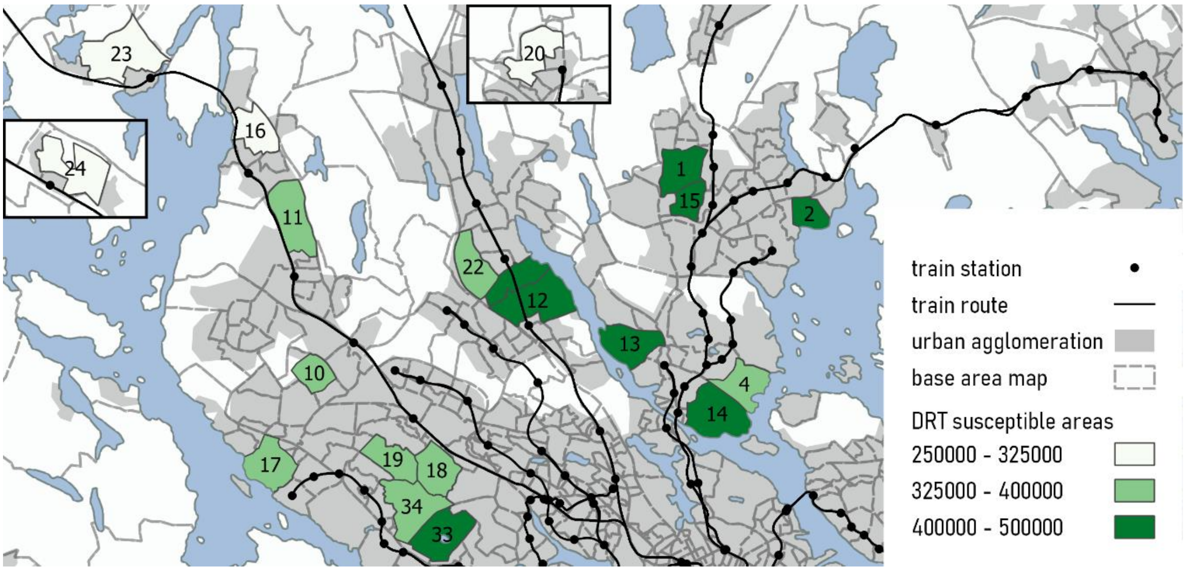


FIGURE 23. Location of the suitable areas to implement DRT in the north of the inner city, with household medium income (in SEK/year)

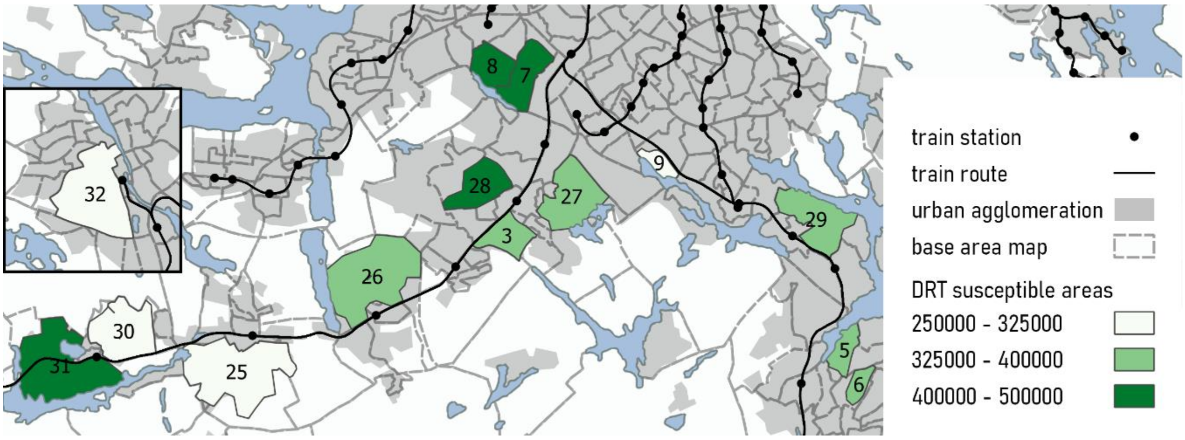


FIGURE 24. Location of the suitable areas to implement DRT in the south of the inner city, with household medium income (in SEK/year)

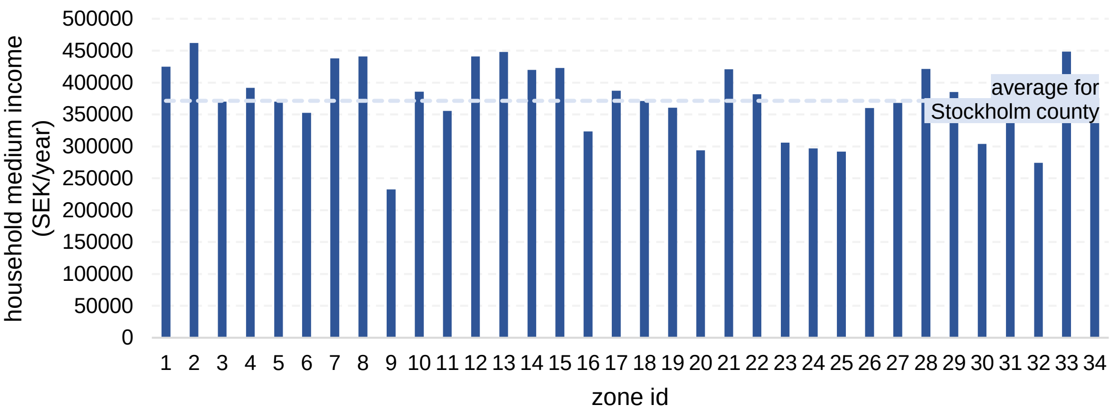


FIGURE 25. Household medium income for each area suitable to implement DRT

According to the hourly demand density, generally the closer a zone is to the inner city of Stockholm, the higher that demand it, with the exception of zones like the Södertälje (32), with urban agglomerations of a certain size. When talking about the household medium income, there is a pattern in which residential areas with a low population density show a medium income above the rest, happening this in the corridors around the Roslagsbanan, with zones 1, 2, 13, 14, 15, or in other areas like Huddinge – Vistaberg (28) or Rönninge – Uttringe (31)

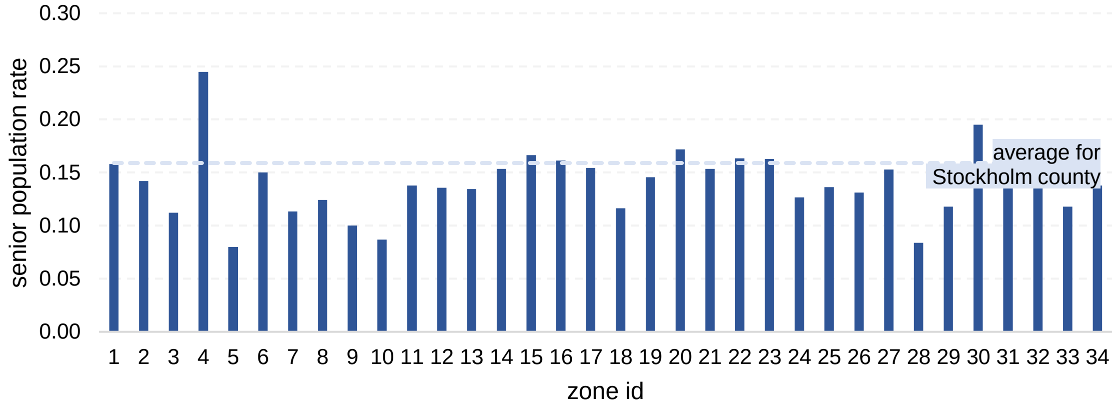


FIGURE 26. Senior population rate for each area suitable to implement DRT

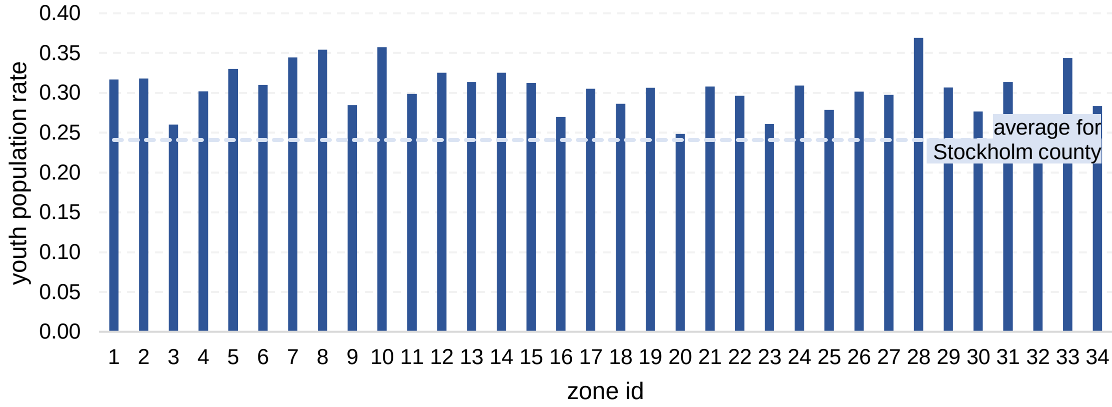


FIGURE 27. Youth population rate for each area suitable to implement DRT

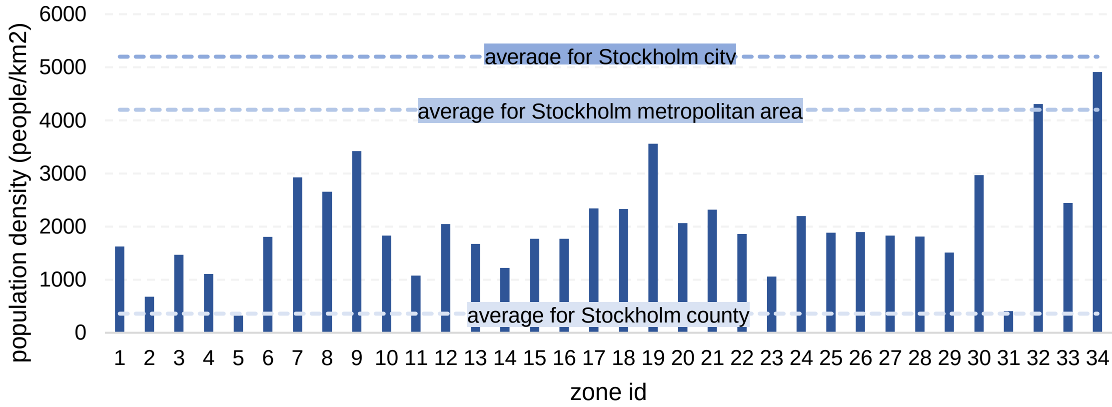


FIGURE 28. Population density for each area suitable to implement DRT

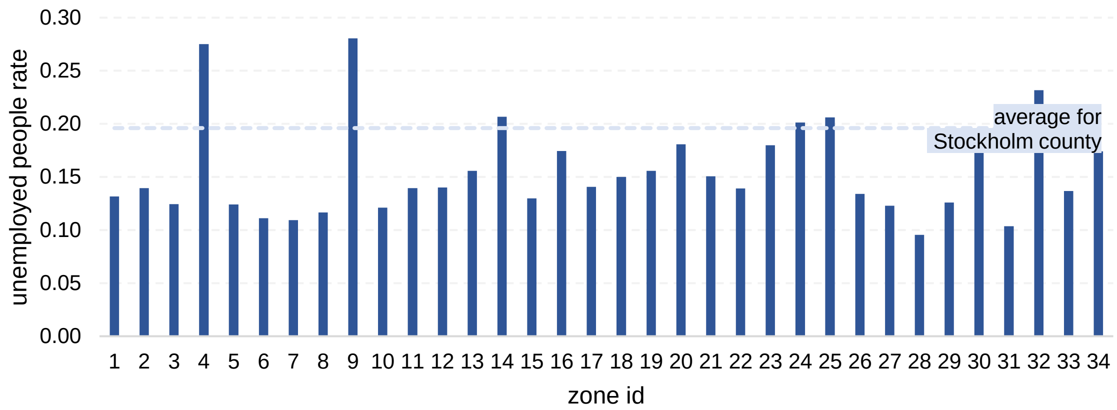


FIGURE 29. Unemployed people rate for each area suitable to implement DRT

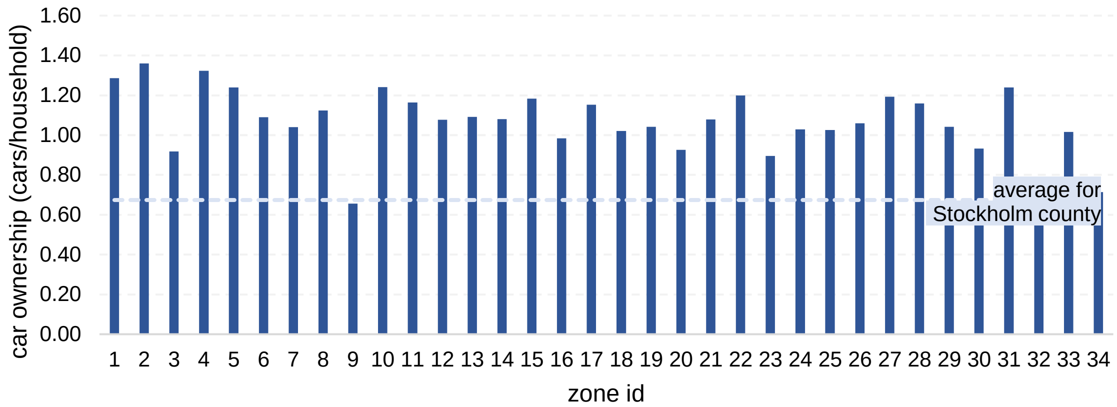


FIGURE 30. Car ownership per household for each area suitable to implement DRT

The figures 26 to 30 represents the socioeconomic variables with relation to the demand of demand responsive transport. The urban configuration and access to transit was used as a filter to determinate the areas suitable to implement the DRT service but the socioeconomic variables are not used as a filter to exclude zones from the later analysis performed. The values of that variables simply suppose an indicator of, in case of a certain zone is selected to implement the DRT service, predict the suitability of its inhabitants to use them. Zones with a higher senior density, higher youth density, smaller population density, higher unemployment density, lower medium income and lower car ownership per household are more suitable to use demand responsive transport, so these factors would be important when there is a need of choosing between zones in which the DRT is classified as the optimal operating service.

5. Analytical model

The objective of implementing this analytical model is to obtain which is the optimal operating strategy, between fixed routes (FR) and demand responsive transport services (DRT), operated as door-to-door, for each one of the areas suitable to implement DRT and for each one of the stages that will be considered according to automation and electrification. This analytical approach has widely been used for the study of public transport systems, from a theoretical perspective (Daganzo, 2010) (Badia, Estrada, & Robusté, 2014) (Badia H. , 2019) to the design of real bus networks (Estrada, Roca-Riu, Badia, Robusté, & Daganzo, 2011) (Estrada, Robusté, Amat, Badia, & Barceló, 2012).

The selection of the 34 zones in the previous section of areas suitable to implement DRT does not indicate that a DRT service is optimal in them and being optimal or not will depend on several parameters introduced in this analytical model, that varies between each zone.

5.1. Model design

The analytical model proposed is based on the one presented in (Badia & Jenelius, 2020a and 2020b) but with adaptations in order to make it more realistic and also to compare it with the simulation carried out to validate the results.

The model environment is based in areas idealized as a rectangle with length D_L (km) and width D_W (km) that it is at D_R (km) from the station, as shown in Figure 31. These lengths have different values for each one of the zones studied. The obtention of the areas as idealised rectangles is explained later in this section.

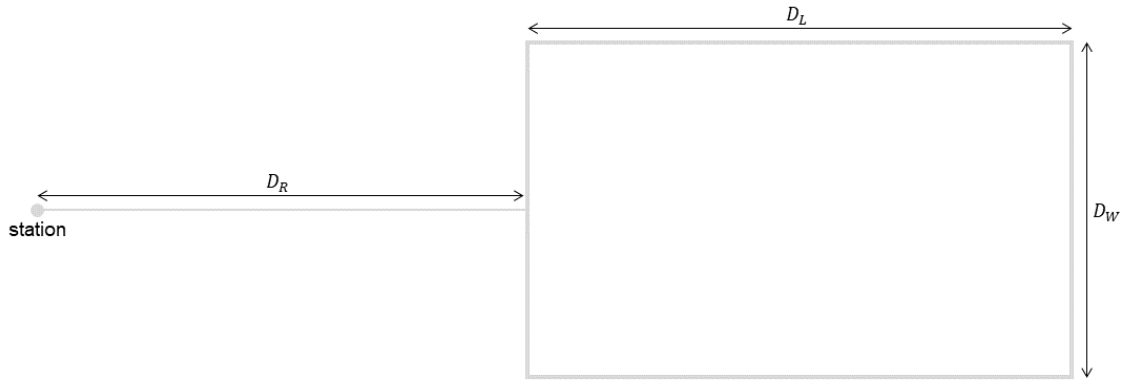


FIGURE 31. Scheme for feeder service between a transit station and a service area

There are more fixed variables, as the ones shown in Table 15, where although most of the fixed parameters maintain its values, some has changes (the values with * indicates that there is a different value for each one of the zones studied and they are shown in Appendix A).

One of the changes is the introduction of a factor γ_r for each area to correct the street pattern, initially conceived as a grid, to get more realistic values, as the streets does not follow that pattern in the cases studied.

As well as D_L, D_W and D_R with different values for each one of the zones studied, the hourly demand density and the value of time are different for each zone and their values are shown in Appendix A.

The value of time is obtained from the values of the household medium income (presented in Table 14). The household median income in Sweden in 2018 (most recent information) is 371400 SEK (Statistiska centralbyrån, 2020) and the value of time for users in the Swedish case is defined equal to 7.15€/h (Trafikverket, 2018) (assuming 1 € = 10.4478 SEK). With it, the relation to obtain the value of time is:

$$VoT_{zone} = household\ medium\ income_{zone} \cdot 7.15/household\ medium\ income_{Swerden} \quad (1)$$

TABLE 15. Fixed input variables common for both operating strategies

fixed variables			
var	***unit***	**input parameter**	**value**
D_L	*(km)*	longitudinal dimension	*
D_W	*(km)*	transversal dimension	*
D_R	*(km)*	road length area to station	*
$\boldsymbol{\delta}$	*(pax/km²-h)*	hourly demand density	*
p	-	portion of travels area to station	0.5
$\boldsymbol{\gamma_r}$	-	route factor	*
n_a	-	number of assignments during inner route	1
VoT	*(€/h)*	value of time	*
v_w	*(km/h)*	walking speed	4
v	*(km/h)*	cruising speed	30
$\boldsymbol{\tau_s}$	*(h)*	dwell time	15/3600
$\boldsymbol{\tau_b}$	*(h)*	boarding/alighting time	2/3600
hs	*(h)*	safety waiting time	4/60
fs		home waiting factor time	1/6

For the FR there are three decision variables that characterize the system, being two of them geometrical, such as stop spacing and line spacing, and one that determines the level of service from a schedule perspective, the headway, as shown in Table 16. The scheme of the fixed routes in also shown with its decision variables in Figure 32.

TABLE 16. Decision variables for fixed routes (FR) services

decision variables		
var	***unit***	**input parameter**
H_l	*(h)*	headway
S_s	*(km)*	stop spacing
S_l	*(km)*	line spacing

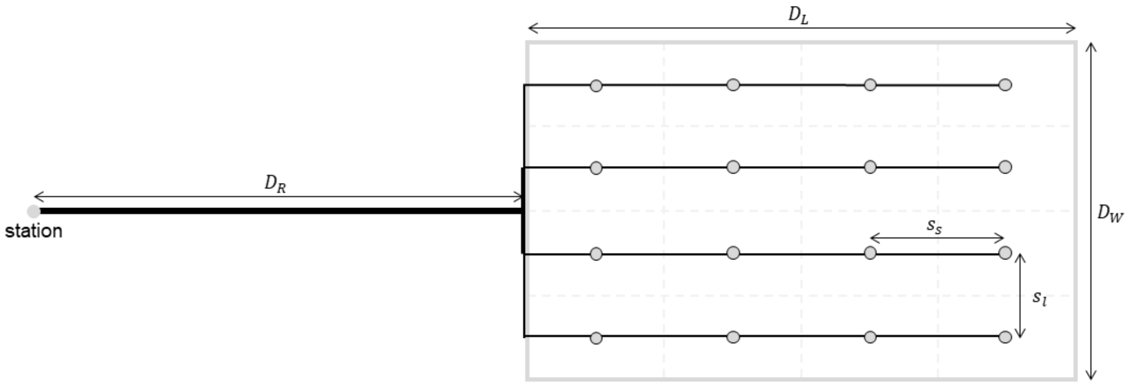


FIGURE 32. Scheme for feeder service as a fixed-route system

Something analogue is also implemented for the DRT case, with three decision variables for characterizing the system. The service headway fixes the frequency with which the buses serve one subzone and the variables L_{sa} (km) and W_{sa} (km) represents respectively the length and width of each one of the subzones considered in the operation of the service.

TABLE 17. Decision variables for demand responsive transport (DRT) services

decision variables		
var	***unit***	**input parameter**
$\mathbf{H_{sa}}$	*(h)*	headway
$\mathbf{L_{sa}}$	*(km)*	length of the subzone served
$\mathbf{W_{sa}}$	*(km)*	width of the subzone served

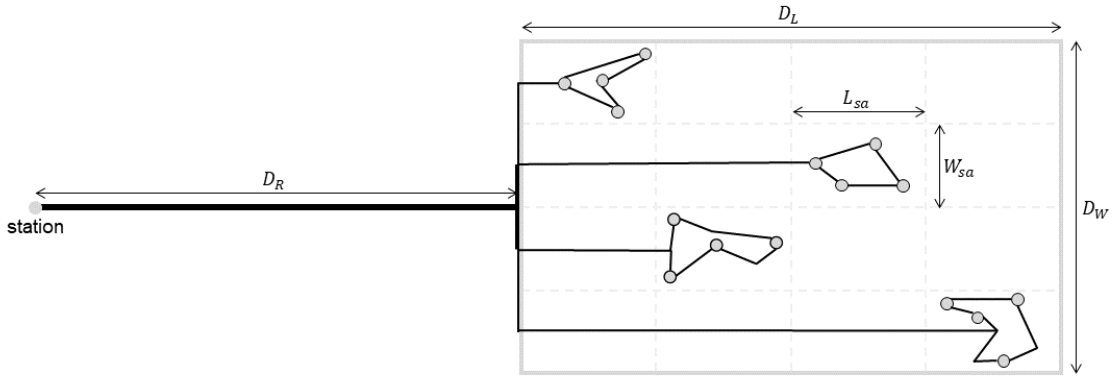


FIGURE 33. Scheme for feeder service as a door-to-door system

5.2. Stages considered

As it is laid out in section 2 and explained in detail in (Badia & Jenelius, 2020b), the technology electrification and automation of vehicles is not fully developed and its process consists of several stages from an initial one, in which the technology development is considered as it is currently, until a final stage if fully implementation of both technologies with its costs reduction and also going through an intermediate stage. It is also considered as a benchmark the current situation but with vehicles in which automation and electrification is not an applied technology.

TABLE 18. Stages considered according to automation and electrification

stage		**automation**	**electrification**
0 - CV	*conventional*	no	no
1 - AV_C	*current*	drivers required as in current vehicles	current electric vehicles
2 - AV_I	*intermediate*	remote driving from a control centre	intermediate electric vehicles
3 - AV_F	*final*	no drivers required	final electric vehicles

5.3. Cost structure

The model optimizes the system total cost for FR and DRT operating strategies. The costs are divided into agency costs and level of service perceived by users and they are derived from:

TABLE 19. Components of the agency costs and level of service perceived by users calculated and optimised in the analytical model

agency costs			level of service perceived by users		
K	*(km)*	travelled kilometres per hour of operation	**A**	*(h)*	access time
F	*(veh)*	required fleet size per hour of operation	**W**	*(h)*	waiting time
S_V	*(pax/veh)*	bus size or capacity	**R**	*(h)*	cruising time component of the riding time
			S	*(h)*	time at stops component of the riding time

To translate the partial agency costs to monetary costs per passenger they are multiplied by their respective unit cost parameters and divided by the total number of users per hour. The unit cost parameters are obtained with:

$$c_{i,j} = \left(1 + \Delta_{i,j}^{A,a} + \Delta_{i,j}^{E,a}\right) \cdot a_i + \left(1 + \Delta_{i,j}^{A,b} + \Delta_{i,j}^{E,b}\right) \cdot b_i \cdot S_V \qquad (2)$$

Equation 2 and the parameters for each one of the three unit costs in the different stages considered previously are obtained from (Badia & Jenelius, 2020b) having them the values presented in Table 19. The parameters $\Delta_{i,j}^{X,x}$ describes the evolution of unit costs because of the development of electrification and automation of the automobiles. The subscripts and superscripts have the meanings shown in the following table:

TABLE 20. Values for the superscripts X and x and subscripts i and j

superscript				subscript			
X		**x**		**i**		**j**	
A	automation	**a**	size-independent part	**V**	capital hourly cost	**CV**	conventional vehicles
E	electrification	**b**	size-dependent part	**H**	unit operating cost per hour	**C**	current stage
				K	unit operating cost per km	**I**	intermediate stage
						F	final stage

The values for $\Delta_{i,j}^{X,x}$ and x_i and applied in the model are shown in the following tables:

TABLE 21. Values for the parameter introduced to describe the evolution of unit costs because of the technological developments of automobile

	$\Delta_{V,j}^{A,a}$	$\Delta_{H,j}^{A,a}$	$\Delta_{K,j}^{A,a}$	$\Delta_{V,j}^{A,b}$	$\Delta_{H,j}^{A,b}$	$\Delta_{K,j}^{A,b}$	$\Delta_{V,j}^{E,a}$	$\Delta_{H,j}^{E,a}$	$\Delta_{K,j}^{E,a}$	$\Delta_{V,j}^{E,b}$	$\Delta_{H,j}^{E,b}$	$\Delta_{K,j}^{E,b}$
CV	0	0	0	0	0	0	0	0	0	0	0	0
C	3.1164	0	0	0	0	0	0.7955	-0.0302	-0.37	1	-0.2797	-0.37
I	1.714	-0.4798	0	0	0	0	0.4773	-0.0302	-0.37	0.6	-0.2797	-0.37
F	0.3117	-0.7197	0	0	0	0	0.1591	-0.0302	-0.37	0.2	-0.2797	-0.37

TABLE 22. Values of the parameter capturing the size-dependence for the unit cost

	a_V	a_H	a_K	b_V	b_H	b_K
CV, C, I and F	1.5262	34.3308	0.1211	0.1350	0.0573	0.0020

According to the user cost, the access time, waiting time and riding time are weighted based on user perception, being that user perception added in the equation 5 to obtain the monetary user cost per passenger. The values for the weighting of the expected time consumed per user in each stage mentioned is obtained from (Kristoffersson, Berglund, Smuelsson, Almström, & Algers, 2018) and shown in the following table.

TABLE 23. Weights considered for the public transport for the stages of the transit chain

stage of transit chain	terminology in Sampers04	weight	value
access (A)	*anslutningsrestid*	w_A	2
waiting (W)	*första väntetid*	w_w	1.5
riding (R+S)	*restid i fordonet*	w_R	1
transfer	*bytestid*		1.5
number of transfers	*antal byten*		5

Electrification of the feeder system, both being a fixed-route one or a door-to-door, leads to an additional cost related with the infrastructure and that represents the acquisition and installation of charging stations. This cost is added to the agency cost in the equation 4. The number of charging stations is defined as N_{ch} and their expressions are presented in the following sub-sections, as the values for fixed route services and DRT services are different. The hourly cost for each charger is defined as c_{ch}, and has a value of 4.766 €/charger-h.

With the partial costs and their respective unit cost parameters and weights presented, the equation to be optimised is:

$$\min\{Z = C_A + C_U\} \tag{3}$$

$$C_A = [c_K \cdot K + (c_V + c_o) \cdot F + c_{ch} \cdot N_{ch}]/\delta D_L D_W \tag{4}$$

$$C_U = VoT \cdot [w_A \cdot A + w_w \cdot W + w_R \cdot (R + S)] \tag{5}$$

5.4. Fixed routes service

As it has been mentioned previously in this section, the equations presented here are obtained from the model designed in (Badia & Jenelius, 2020a and 2020b), with changes, although they are minimums, in order to adapt it to the aims of this document. For the equations with changes in relation to the original equations, these changes are mentioned after presenting the equations.

Parameters related to electrification are included as the additional time per service cycle to charge the batteries, T_{ch}.

$$T_{ch} = 2(D_L - s_s/2 + D_W/4 + D_R) \cdot f_e / S_{ch} \tag{6}$$

f_e is the energy consumption factor, that follows the equation $f_e = 0.159 + 0.0143 \cdot S_v$ and S_{ch} the charging speed takes a value of $S_{ch} = 450 kWh/h$.

For the partial agency costs, the equations for travelled kilometres per hour of operation (K), required fleet size per hour of operation (F), bus size or capacity (S_V) and the number of charging stations (N_{ch}) are:

$$K = 2(D_L/s_L)(D_L - s_S/2 + D_W/4 + D_R)/H_l \tag{7}$$

$$F = 2(D_L/s_L)[(D_L - s_S/2 + D_W/4 + D_R)/v + \tau_s(D_L/S_s + 1) + \tau_b \delta H_l s_l D_L + T_{ch}]/H_l \tag{8}$$

$$S_V = \max(p, 1-p)\, \delta H_l s_l D_L \tag{9}$$

$$N_{ch} = [2(D_L - s_s/2 + D_W/4 + D_R) \cdot f_e / S_{ch}](D_W/s_l)/H_l \tag{10}$$

For the partial user costs, the equations for access time (A), waiting time (W), and the components of the riding time (cruising time (R) and time at stops (S)) are:

$$A = (s_l + s_s)/4v_w \tag{11}$$

$$W = \min\{H_l/2; h_s + f_s H_l\} \tag{12}$$

$$R = (D_L/2 + D_W/4 + D_R)/v \quad (13)$$

$$S = \tau_s(D_L/2S_s + 1) + (1 - 2p + 2p^2)\tau_b \delta H_l s_l D_L/2 \quad (14)$$

The factor s_f has been eliminated from the equations as the cruising speed is considered the same in the service area than in the road between it and the station.

5.5. Demand responsive transport service

5.5.1. Multiple subzones

The equations for the DRT are obtained from the same source mentioned for the FR service equations. In case of changes in relation to the original equations, these changes are mentioned after presenting the equations.

As with the fixed-route case, parameters related to electrification are included as the additional time per service cycle to charge the batteries, T_{ch}.

$$T_{ch} = (D_L - l_{sa} + D_W/2 + 2D_R + \gamma_r r) \cdot f_e/S_{ch} \quad (15)$$

f_e and S_{ch} take the same values than the ones shown previously.

For the partial agency costs, the equations for travelled kilometres per hour of operation (K), required fleet size per hour of operation (F), bus size or capacity (S_V) and the number of charging stations (N_{ch}) are:

$$K = (D_L D_W/l_{sa} w_{sa}) \cdot (D_L - l_{sa} + D_W/2 + 2D_R + \gamma_r r)/H_{sa} \quad (16)$$

$$F = (D_L D_W/l_{sa} w_{sa})[(D_L - l_{sa} + D_W/2 + 2D_R + \gamma_r r)/v_c + \tau_s(\delta H_{sa} l_{sa} w_{sa} + 2) + 2\tau_b \delta H_{sa} l_{sa} w_{sa} + T_{ch}]/H_{sa} \quad (17)$$

$$S_V = \delta H_{sa} l_{sa} w_{sa} \quad (18)$$

$$N_{ch} = [(D_L - l_{sa} + D_W/2 + 2D_R + \gamma_r r) \cdot f_e/S_{ch}](D_L D_W/l_{sa} w_{sa})/H_{sa} \quad (19)$$

For the partial user costs, the access time will have a value of 0, as the service is conceived as a door to door service, and the equations for waiting time (W) and the components of the riding time (cruising time (R) and time at stops (S)) are:

$$W = p \cdot \min\{[H_{sa} + (\gamma_r r/v_c + (\tau_s + \tau_b)\delta H_{sa} l_{sa} w_{sa})/n_a]/2; h_s + f_s[H_{sa} + (\gamma_r r/v_c + (\tau_s + \tau_b)\delta H_{sa} l_{sa} w_{sa})/n_a]\} + (1 - p) \cdot \min\{H_{sa}/2\,; h_s + f_s H_{sa}\} \quad (20)$$

$$R = [(D_L - l_{sa})/2 + D_W/4 + D_R + \gamma_r r/2]/v_c \quad (21)$$

$$S = \tau_s(\delta H_{sa} l_{sa} w_{sa}/2 + 1) + \tau_b \delta H_{sa} l_{sa} w_{sa}(1 - p + p^2) \quad (22)$$

As with the FR service, the factor s_f has been eliminated for the same reason that in that service.

5.5.2. Unique subzone

For the validation purposes that will be developed in following sections of this document, an adaptation of the model for DRT considering a unique subzone with equal area than the service area has been performed. The equations in 5.5.1 are recalculated with some changes.

There are no decision variables that can be optimised, as their values come from the optimization in the model with the consideration of multiple zones. The values of l_{sa} and w_{sa} are now fixed and equal to the values of D_L and D_W respectively. The value of H_{sa} is calculated as:

$$H_{sa,unique} = H_{sa,multiple}/N_{zones} \quad (23)$$

With the decision variables with fixed values, the equations for the user costs and agency costs are calculated, with changes in the following ones:

$$T_{ch} = (2D_R + \gamma_r r) \cdot f_e / S_{ch} \tag{24}$$

$$K = (2D_R + \gamma_r r)/H_{sa} \tag{25}$$

$$F = [(2D_R + \gamma_r r)/v_c + \tau_s(\delta H_{sa} l_{sa} w_{sa} + 2) + 2\tau_b \delta H_{sa} l_{sa} w_{sa} + T_{ch}]/H_{sa} \tag{26}$$

$$N_{ch} = [(2D_R + \gamma_r r) \cdot f_e/S_{ch}](D_L D_W / l_{sa} w_{sa})/H_{sa} \tag{27}$$

$$R = [(D_R + \gamma_r r/2]/v_c \tag{28}$$

The equations for S_V, W and S are recalculated but with no changes for the adaptation of unique zone with respect to the equations 18, 20 and 22

5.6. Conversion to rectangle of the zones

This analytical model considers areas idealized as a rectangle with length D_L (km) and width D_W (km), what in practice does not represent the reality as the zones studied follows irregular boundaries, that were obtained in the previous section, that, although to a greater or lesser grade can look like a rectangle, in none of the cases have the shape of a perfect rectangle.

The algorithm 'Oriented minimum bounding box' is executed in QGIS, calculating the minimum area rotated rectangle for each feature in the input layer (QGIS Project, 2020) to the zones selected in section 4 and shown in Appendix A.

FIGURE 34. Original zones represented with its minimum rectangle (L_1, W_1) and corrected rectangle (L_2, W_2)

The minimum rectangle, with a length L_1 and a width W_1, has an area A_1 bigger than the area of the original zone A_{zone}. This could suppose a problem when it is introduced in the analytical model, as the demand density is dependent on the area and a bigger area would imply a greater number of passengers, not being it representative of a real situation.

A correction is proposed in order to maintain a rectangle proportional to the minimum obtained, being it representative for the zones taken into consideration, but at the same time maintaining the area of the original zone, being it representative in terms of the demand.

$$L_2 = \sqrt{A_{zone} \cdot L_1/W_1} \tag{29}$$

$$W_2 = A_{zone}/L_2 \tag{30}$$

The corrected rectangles, with a length L_2, width W_2 and an area $A_2 = A_{zone}$, are the ones that are introduced in the analytical model as an input parameter.

5.7. Calculation of the route factor

An important parameter to make the analytical model more realistic, the route factor γ_r, is included to adjust the length of the route to the street pattern, as the one considered for the calculation of the route length (r) is with an assumption of an infinite grid street pattern.

5.7.1. Definition

The equations and formulation to define the route factor chosen is presented in (Chandra & Quadrifoglio, 2013). The reason to choose this formulation, and no other available indicators like the gamma index or the transportation planning indicator, is because the ease to compute it and the direct relation between its value and the transit performance. It is also important to choose this indicator that both the agency costs (related to the total distance travelled) and level of service perceived by users (related to the riding time and waiting time) are weighted in its formulation.

The connectivity indicator defined relates the average expected shortest path (S_a) and the smallest possible average shortest path distance (S_{min}).

For the calculation of the average expected shortest path, the demand has been assumed uniformly among the whole area, and therefore uniformly among the stops, and it is defined by:

$$S_a = T/[N(N-1)] = (\sum_{i=1}^{N}\sum_{j=1}^{N} d_{ij})/[N(N-1)]\ , j \neq i \tag{31}$$

T is the sum of all the shortest paths among all the potential nodes N, in which the relation to the total travel distance is directly included and proportional and the service components are too though the expected riding time and waiting time. The term d_{ij} represents the shortest path between any two nodes i and j.

A network with perfect connectivity must be defined to compare it with the real pattern of streets and obtain the relation between them. An infinitely dense grid network is assumed as the one with the perfect connectivity, considering in that case the possible average shortest path distance as:

$$S_{min} = (D_L + D_W)/3 \tag{32}$$

The connectivity indicator is defined as:

$$connectivity\ indicator\ (C.I) = S_{min}/S_a \tag{33}$$

The range of values for the C.I. goes from 0 to 1. A network with perfect connectivity takes a value of 1 for the connectivity indicator, being the index directly proportional to the transit performance, what indicates that smaller values of the indicator are for networks with a worse connectivity. The route factor is defined as the inverse of the connectivity indicator:

$$\gamma_r = 1/C.I = S_a/S_{min} \tag{34}$$

The values of the route factor with this definition can vary from 1 to infinite, what will adjust the length of the routes by the multiplication of its values times this factor.

5.7.2. Procedure for the calculation

In the procedure for calculating the route factor the information described below has been used.

- Geographical information
    - Road network in the Stockholm County. The geometry represents the roads based on the Swedish standard SS637004 for road network connection (Stockholms Stad, n.d.)
    - Areas suitable to implement DRT service, as created in previous sections of this document.

The first step for the calculation of the route factor is to distribute potential stops for the on-demand service among the network included in the area suitable to implement the DRT. This has been executed in QGIS with the algorithm 'Points along geometry', which creates points at regular intervals along line. The chosen interval is 50m, small enough to consider that this is a door to door service and the access time and distance can be assumed negligible.

After it, a graph is built to calculate the shortest path between nodes. The potential stops created are connected to the existing street network with the algorithm 'Connect nodes to lines' and the graph with 'Build graph', both also in QGIS. Two shape files are obtained, one of points, with an id as attribute, and another of lines, with attributes of the point id from and point id to which each line is directed.

TABLE 24. Input, procedure, and output for the creation of the graph

input	procedure	output
Shape file (.shp) containing the road network Shape file (.shp) containing areas suitable to implement DRT service	Execution of 'Points along geometry' (distance 50m) in the road network inside the areas suitable for DRT Execution of 'Connect nodes to lines' Execution of 'Build graph'	Shape file (.shp) of nodes (potential stops) with id attribute Shape file (.shp) of lines (links between nodes) with attributes of id from and id to

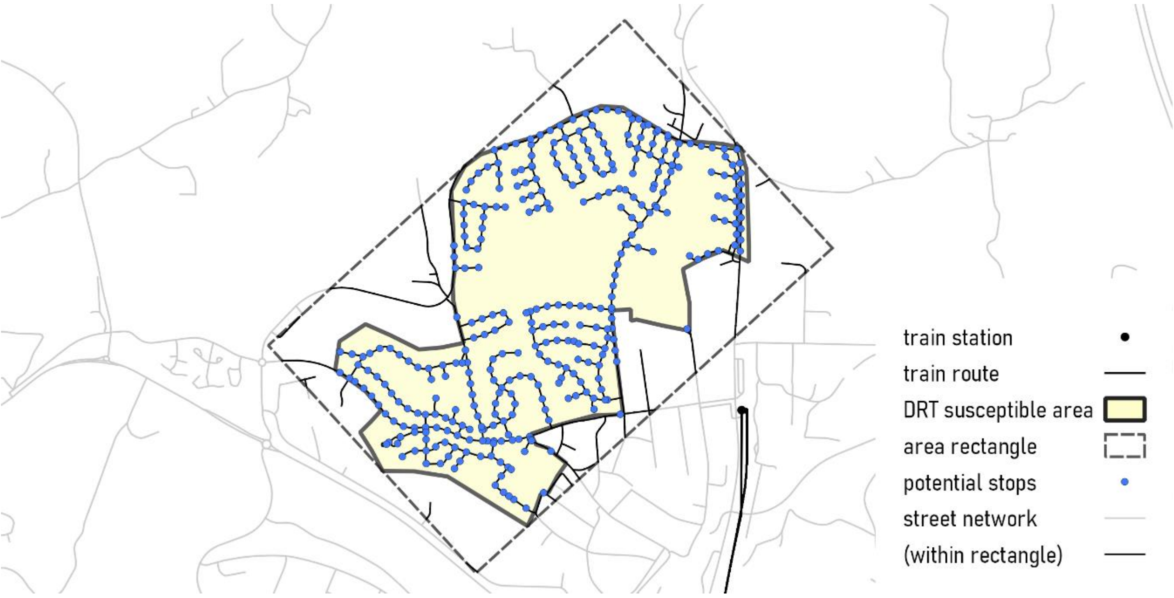


FIGURE 35. Potential stops and network for the calculation of the route factor

Once the elements needed for the graph are obtained, the information contained in these shape files is introduced to the code that has been created in MATLAB, that includes the Dijkstra's algorithm that finds the shortest paths between nodes in a graph, and that provides the route factor for each one of the areas suitable to implement DRT.

The results of the route factor are shown in the next section, with the rest of results obtained in the analytical model

TABLE 25. Input, procedure, and output for the obtention of the route factor

input	procedure	output
Shape file (.shp) of nodes (potential stops) with id attribute Shape file (.shp) of lines (links between nodes) with attributes of id from and id to Shape file (.shp) containing areas suitable to implement DRT service	Execution of MATLAB codes (including the execution of the Dijkstra's algorithm)	Values of route factor γ_r for each area suitable to implement DRT service

5.8. Results

In Table 26 the inputs with different value for each one of the zones studied in the analytical model, as shown in Table 15, are presented.

The longitudinal dimension (D_L) and transversal dimension (D_W) are obtained as it was explained in section 5.6, the road length from area to station (D_R) is a direct distance obtained in QGIS, the route factor (γ_r) is the one calculated with the procedure described in section 5.7, hourly demand density is the same than the one presented in Table 14 and the value of time calculated with the equation 1:

TABLE 26. Input parameters that have different values for each zone and used in the analytical model

id	zone name	D_L *(km)*	D_W *(km)*	D_R *(km)*	γ_r *(-)*	demand density *(pax/km^2-h)*	VoT *(€/h)*
1	Ensta - Ella	1.17	1.35	0.37	1.6883	75.52	8.19
2	Viggbyholm	0.89	1.04	0.51	1.193	50.10	8.90
3	Huddinge - Solgård	1.26	1.12	0.37	1.3568	77.09	7.13
4	Södra Djursholm	1.41	1.09	0.44	1.3142	66.15	7.55
5	Vega - Norrby	1.41	0.64	1.01	1.3136	6.76	7.13
6	Vega - Söderby	1.22	0.48	1.42	1.2187	77.48	6.80
7	Långsjö	1.85	1.00	0.55	1.3562	162.24	8.44
8	Herrängen	1.06	1.29	0.54	1.2022	130.65	8.50
9	Havsörnstorget	1.14	0.50	1.48	1.5479	46.02	4.48
10	Ormbacka - Skälby gård	0.92	1.11	1.06	1.0937	89.37	7.44
11	Jakobsberg - Berghem	2.24	0.99	0.76	1.9695	94.40	6.85
12	Helenelund	1.27	1.99	0.20	1.3955	106.53	8.49
13	Nora - Klingsta	1.25	1.43	0.59	1.4555	102.36	8.64
14	Stocksund	1.79	1.33	0.27	1.2191	76.73	8.09
15	Ellagård	0.80	1.09	0.33	1.3947	95.22	8.15
16	Kallhäll	1.45	1.06	0.62	1.6572	108.72	6.23
17	Hässelby	1.36	1.33	0.39	1.5782	123.58	7.46
18	Sundby - Flysta	1.38	1.15	0.88	1.1984	130.15	7.16
19	Nälsta	0.86	1.65	0.94	1.3586	182.19	6.95
20	Märsta	1.06	1.66	0.44	2.0943	107.98	5.67
21	Fågelsången - Skansen	0.72	1.80	0.31	1.7573	117.31	8.11
22	Töjnan	0.91	1.79	0.51	1.0859	99.26	7.35
23	Kungsängen	1.53	2.02	0.20	2.0154	92.70	5.89

24	Bro	1.26	1.92	0.42	2.0907	64.39	5.72
25	Tumba	2.00	2.69	0.24	1.6601	117.56	5.62
26	Tullinge	1.88	2.77	0.27	1.2704	91.38	6.94
27	Huddinge - Kynäs	1.54	1.85	0.69	1.348	63.96	7.09
28	Huddinge - Vistaberg	1.05	1.82	0.45	1.6768	65.95	8.12
29	Trångsund	1.33	2.06	0.22	1.5669	61.36	7.43
30	Rönninge - Salems	1.77	1.71	0.19	1.9062	117.51	5.86
31	Rönninge - Uttringe	2.45	1.99	0.04	1.8315	27.48	7.83
32	Södertälje	1.90	2.43	0.09	1.6031	248.63	5.28
33	Ängby - Bromma	1.64	1.24	0.20	1.3621	139.47	8.64
34	Råcksta - Beckomberga	1.52	1.51	0.39	1.9637	217.22	6.78

Once the results from table 24 are introduced in the model for the different stages for automation and electrification, the system total cost for each stage and each operation strategy is obtained, being possible then to choose which one is the optimal. From a total of 34 zones studied, 1 zone is cheaper in the conventional (0) stage with DRT than FR, 0 zones in the current (1) stage, 4 zones in the intermediate (2) stage and finally 12 zones in the final (3) stage.

TABLE 27. Results for the four stages of automation and electrification considered and the two operating strategies for each zone and selection of the optimal operating strategy

	FR service				**DRT service**				**optimal operating strategy**			
id	$\boldsymbol{CV}$	$\boldsymbol{AV_C}$	$\boldsymbol{AV_I}$	$\boldsymbol{AV_F}$	$\boldsymbol{CV}$	$\boldsymbol{AV_C}$	$\boldsymbol{AV_I}$	$\boldsymbol{AV_F}$	$\boldsymbol{CV}$	$\boldsymbol{AV_C}$	$\boldsymbol{AV_I}$	$\boldsymbol{AV_F}$
1	3.09	3.18	2.73	2.34	3.76	3.92	3.11	2.48	FR	FR	FR	FR
2	3.70	3.79	3.25	2.76	3.63	3.80	3.00	2.33	DRT	FR	DRT	DRT
3	2.75	2.83	2.43	2.08	3.14	3.29	2.60	2.04	FR	FR	FR	DRT
4	3.02	3.11	2.67	2.30	3.38	3.54	2.81	2.23	FR	FR	FR	DRT
5	5.28	5.45	4.59	3.91	5.35	5.59	4.41	3.53	FR	FR	DRT	DRT
6	3.16	3.23	2.86	2.42	3.46	3.61	2.94	2.40	FR	FR	FR	DRT
7	2.78	2.85	2.50	2.19	3.40	3.55	2.86	2.27	FR	FR	FR	FR
8	2.88	2.96	2.55	2.20	3.14	3.28	2.60	2.04	FR	FR	FR	DRT
9	2.24	2.30	2.01	1.74	2.82	2.96	2.38	1.93	FR	FR	FR	FR
10	3.13	3.22	2.76	2.37	3.22	3.37	2.69	2.14	FR	FR	DRT	DRT
11	2.79	2.87	2.50	2.18	3.92	4.09	3.33	2.69	FR	FR	FR	FR
12	2.93	3.01	2.60	2.24	3.39	3.54	2.83	2.22	FR	FR	FR	DRT
13	3.14	3.22	2.78	2.40	3.67	3.83	3.07	2.45	FR	FR	FR	FR
14	3.05	3.14	2.71	2.35	3.39	3.54	2.83	2.24	FR	FR	FR	DRT
15	2.85	2.94	2.50	2.13	3.13	3.28	2.57	1.98	FR	FR	FR	DRT
16	2.41	2.48	2.13	1.84	3.17	3.31	2.63	2.12	FR	FR	FR	FR
17	2.59	2.67	2.31	1.99	3.27	3.42	2.72	2.15	FR	FR	FR	FR
18	2.69	2.76	2.39	2.08	3.11	3.25	2.61	2.09	FR	FR	FR	FR
19	2.53	2.60	2.24	1.94	3.01	3.15	2.52	2.00	FR	FR	FR	FR
20	2.23	2.30	1.97	1.68	3.12	3.27	2.62	2.07	FR	FR	FR	FR
21	2.81	2.90	2.47	2.11	3.41	3.56	2.82	2.20	FR	FR	FR	FR
22	2.83	2.91	2.49	2.13	2.91	3.04	2.40	1.88	FR	FR	DRT	DRT
23	2.33	2.40	2.06	1.77	3.27	3.42	2.75	2.19	FR	FR	FR	FR
24	2.55	2.62	2.26	1.93	3.48	3.64	2.91	2.34	FR	FR	FR	FR
25	2.24	2.31	2.00	1.74	3.09	3.23	2.59	2.08	FR	FR	FR	FR
26	2.78	2.86	2.47	2.15	3.29	3.45	2.76	2.23	FR	FR	FR	FR

27	3.14	3.23	2.78	2.40	3.62	3.77	3.02	2.45	FR	FR	FR	FR
28	3.30	3.40	2.91	2.49	3.90	4.06	3.25	2.61	FR	FR	FR	FR
29	3.05	3.14	2.69	2.31	3.62	3.78	3.01	2.42	FR	FR	FR	FR
30	2.18	2.25	1.94	1.68	3.10	3.25	2.59	2.07	FR	FR	FR	FR
31	3.78	3.87	3.42	2.94	4.76	4.96	4.00	3.26	FR	FR	FR	FR
32	1.76	1.82	1.58	1.38	2.54	2.67	2.11	1.67	FR	FR	FR	FR
33	2.74	2.81	2.44	2.12	3.26	3.40	2.70	2.12	FR	FR	FR	DRT
34	2.65	2.72	2.34	2.01	3.34	3.50	2.78	2.25	FR	FR	FR	FR

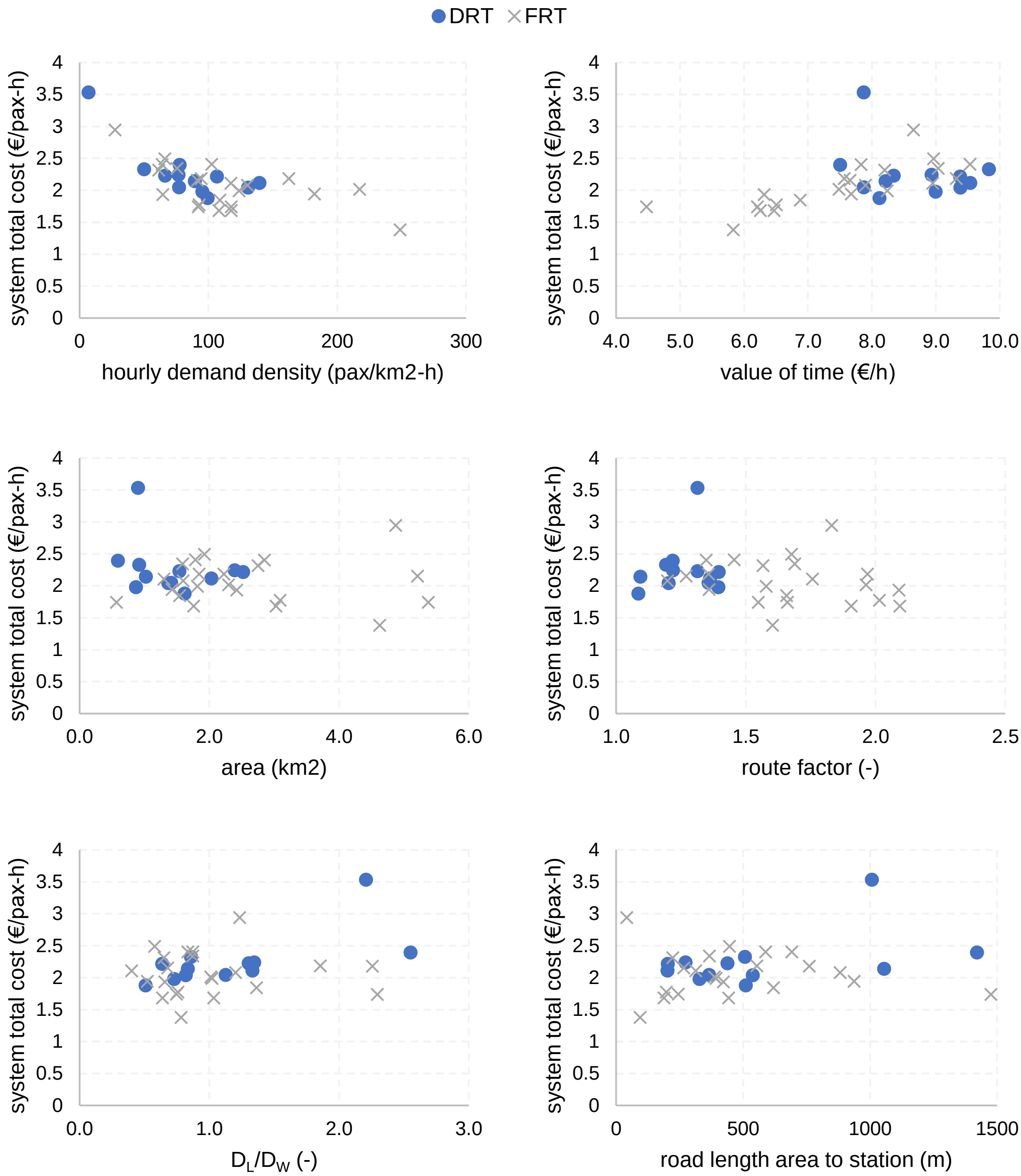


FIGURE 36. System total cost versus the variables that changes their values depending on the zone studied with optimal system total cost for the stage 3

The results depicted in Figure 36 lead to conclude from the analytical model that in the application of it to the real zones selected, some of the parameters influence to determine if the optimal operating system is with FR or DRT.

The road length between the station and the zone and the relation between D_L and D_W do not influence as in all the range of values for those two variables there are both zones with optimal operating system DRT and FR. However, all the zones in which the DRT is the optimal operating system for this stage have a hourly demand density with values smaller than 140pax/km^2-h, values of time higher than 7.50€/h and values for the route factor smaller than 1.40.

6. Simulation

A simulation in a commercial software, in this case the selected has been PTV VISUM 2020 (SP 1-9), has been considered to complete the purpose of this document, validating the results given by the analytical model implemented in the cases considered and obtaining results for the simulation of the zones obtained that are suitable to implement the demand responsive transport service in the metropolitan area of Stockholm.

The initial objective was to be able to simulate firstly the demand responsive transport in an idealised area, to validate the results of the analytical model, for later applying it in the zones obtained that are suitable to implement the DRT service from the section 5 and, in a final step, implement in some of them the DRT service (as a first/last mile feeder system) in combination with public transport, to evaluate what are its impacts in terms of cost for the user and agency costs.

The extension for simulating DRT in VISUM is not available in the functionalities provided to the KTH and obtaining it was not a quick process, specially due to the current global situation with the corona crisis, as the new license with the add-on for ride-sharing was sent physically from another country. These problems with the simulation made difficult to carry on what was initially planned due to lack of time, and the scope that has been achieved finally has been reduced, with no evaluation of the DRT service in combination with public transport, and just the evaluation of the results in VISUM for the areas with suitability to implement DRT under the conditions of the final stage (3).

6.1. Basis for simulating demand responsive transport

As the demand responsive transport systems are getting more attention as an alternative to conventional systems to get more passengers to the public transport system, the need to have a better planning when implementing a DRT system requires realistic simulations, taking into account the agent and user costs.

When simulating a demand responsive transport system, an important requirement is to combine optimization, what means to incorporate the allocation of requests to vehicles, and simulation, incorporating the movement of people and vehicles (Ronald, Thompson, & Winter, 2015). According to the mentioned paper, the components considered in a DRT simulation are the demand, supply, and the algorithms to manage them, to finally create outputs.

Depending on the scope needed in the problem, the components to consider in the DRT simulation are different. For this document, the model scope is the simulation of DRT alone, as the objective is to validate the comparison of the different operational systems, what can be done in a short-term horizon, as indicated in Table 28.

TABLE 28. Simulation scopes, time horizons, demand, and supply from (Ronald, Thompson, & Winter, 2015)

scope	**time horizon**	**demand**	**supply**
DRT alone	short (*operational)*	Trips	trip schedule
DRT integrated with other modes	medium (*tactical)*	Mode choice, daily activity plan	n of buses, operating hours
DRT integrated with other modes and land-use	long *(strategic)*	Residential choice, car ownership, socioeconomic changes	n of buses, operating hours, service area

6.1.1. Demand

According to the demand as an input, it is considered as a request, being it an uncertain element in the simulation of demand responsive transport, while it is a certain element, normally the number of trips, in the typical approach in transport models.

When it is referred to individuals instead of requests, the difference is that the requests can be assumed to belong to a separate individual or to more than an individual at the same time.

The travel intention and mode choice are also important (when talking about modelling with the DRT as only choice, if the service cannot serve the request, the individual will not be able to travel).

6.1.2. Supply

In the transport supply vehicles and the network are the main features to have as an input in the simulation.

On the one hand, the vehicles need to be defined to be introduced as an input, with its demand period and capacity (number of seats).

On the other hand, the transport network is represented by the environment in which the DRT system is giving its service. The network gives information about the times spent between the different nodes presented.

In the supply it is also important to consider the operation of the system, which includes:

- Pre-booking time. The requests can be booked in advance or can be booked in the same time that the travel is desired.
- Flexibility. Both the time and the route can be fixed or not, so it is possible to find several operation systems according to the flexibility, from ones with fixed-route and fixed-time to others with flexible-route and flexible-time, what is a pure on-demand system.
- Pick-up and drop-off locations. The operation can be many-to-many, if it is possible to use any node as pick-up or a drop-off node, or many-to-one if the pick-up/drop-off node for all the requests considered is always the same one, usually a point of interest in terms of the transport system.

6.1.3. Algorithms

The problem solved in the optimization of the DRT is the dial-a-ride problem (DARP), being it a modification of the pickup and delivery problem, the vehicle routing problem (VRP), and the vehicle routing problem with pickup and delivery (VRPPD) (Ronald, Thompson, & Winter, 2015). In the DARP problem the agent costs are minimized, and the quality of service experienced by the users is maximized.

6.2. VISUM operation procedures

PTV VISUM is a software that, as many other transportation modelling systems, allows to model private and public transport, unifying a demand model, network model and impact models to get different results. Not all the transport planning software allows to simulate ride-sharing services, as it is an alternative to conventional systems which implementation is taken as a part of the future mobility ecosystem, with the arrival of automated vehicles or the electrification of them.

Although there are more software that allows to simulate DRT systems, PTV VISUM has been chosen because it is one of the most used transport planning software, with newly added characteristics to implement the simulation of future mobility services such as ride-sharing is, the intuitiveness and familiarity when using it according to the acquired knowledge in other transport planning software and the possibility of simulate ride-sharing as a feeder service por first/last mile, although as it was explained previously, certain problems with the license frustrated this objective.

DRT does not require a timetable, fixed route or fixed stops and the individuals are able to make trip requests, that includes certain conditions about place or time. To plan the service given to that trip requests, the modelling at a node and time level is necessary, requiring to use microscopic modelling features that have been implemented in recently launched versions of VISUM.

The ride-sharing systems simulation basis in VISUM follows the three steps explained in the previous sub-section, with a demand to be satisfied by the supply introduced and which through the assignment-dispatching gives the results of the simulation.

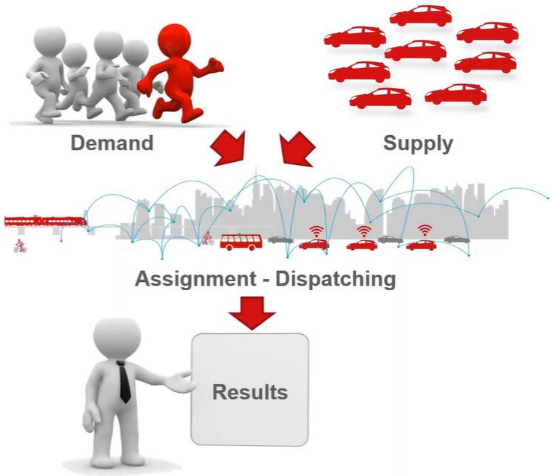


FIGURE 37. Scheme of the ride-sharing procedure in VISUM.
[Source: PTV Group Traffic Youtube account, https://www.youtube.com/watch?v=7StOJk2evJc]

In the simulation of the DRT service, two procedures must be added in the procedure sequence, to create the mentioned demand, add the supply and run the assignment-dispatching. The procedures needed are:

- Generate trip requests
  This procedure disaggregates the demand assigned to a zone to different trip requests, in a stochastic process for the location and time, disaggregating the demand to node level. The trip requests are created between nodes during a selected timespan.
- Tour planning
  This is the procedure where supply and assignment are executed. The fleet size and vehicle specification are set (including seats capacity or parameters related with electrification) as well as the pick-up and drop-off (PUDO) points. The trip requests are transferred to the dispatcher, that determines the vehicles that are available and picks the best vehicle with estimated lowest costs to serve the trip request.

In the following subsections the parameters needed as an input in both procedures are explained with detail.

6.2.1. Trip requests generation

Demand responsive transport has as characteristics the quick accessibility to the nodes of the pick-up or drop-off and short detours to serve other requests, being that the reason why the demand should be disaggregated from zone level to node level to execute the microscopic simulation (PTV Group, 2020).

The passengers are not supposed to travel together in this simulation, for each passenger corresponds one request, so the 100% of the requests are of one individual.

The pre-booking time and the maximum waiting time define the quality of the supply. The dispatching is affected by the value of these inputs. The value set for the pre-booking time is different for each case simulated, following equation 36, and for the maximum waiting time, a 15min value, as predefined, is maintained.

There is a random seed that controls the disaggregation, being important to run the procedure multiple times with different values for this seed to finally obtain reliable characteristic values.

The start and end nodes are defined with the selection of the nodes linked to a certain zone, by the selection of an attribute created for it, that includes the zone to which every node belongs to.

As the service is conceived as a door to door service, with no access time and distance, and to maintain that characteristic, all the nodes that has demand disaggregated on them are selected as PUDO points.

6.2.2. Tour planning

With the execution of this procedure, the trip requests are linked to the vehicles available, that will depend on the level of service provided with the parameters specified in this procedure.

The demand period hours need to be set, so the tour planning generates the tours of the individual fleet vehicles during the period. The definition of the time required for the pick-up and drop-off per trip-request as well as the fleet (number of vehicles and number of seats per vehicle)

It exists the option to choose if multiple trip requests may share a vehicle, with three parameters to choose for it, maximum detour factor, maximum detour time and detour accepted time. These parameters influence the maximum arrival time with the following equation (PTV Group, 2019):

$$\begin{aligned} &maximum\ arrival\ time \\ &\quad = earliest\ departure\ time + ideal\ travel\ time \\ &\quad + \min\left(\max\left((detour\ factor - 1)\right.\right. \\ &\quad \left.\left.\cdot\ ideal\ travel\ time, always\ accepted\ detour\ time\right), maximum\ detour\ time\right) \end{aligned} \tag{35}$$

The dispatcher algorithm can be optimized in two ways, can minimize the number of vehicles needed or maximize the number of served trip requests.

The tour planning is executed on the network created that includes all the streets and the holding areas and charging areas must be selected. The holding areas can be used for relocation, that indicates that the vehicles move to the nearest holding area after a certain period of inactivity that needs to be set and can be used for starting and end of a tour.

6.3. Simulation of a simplified case. Validation

In order to validate the results obtained from the analytical model, an idealised case is executed. The idealized model is a rectangle with a longitudinal dimension of 2.5 km and transversal dimension of 1.2 km. The distance between the station to the suburban area is 0.5 km. The route factor has a value of 1 as the street pattern follows a grid and the value of the demand density varies between 10 and 500 pax/km^2-h to evaluate the results for different values of it. The value of time is 7.15€ given by the average Swedish case (Trafikverket, 2018). The rest of the input parameters have the same values than the ones given in Table 15.

In VISUM, when simulating DRT, the zone in which that service will operate, can be divided in terms of defining the OD matrix with applying different values for each OD pair, but the fleet introduced to operate in the area will serve all the area, independent of in which subzone the trip request have been originated.

An adaptation of the analytical model considering multiple subzones is performed to consider an analytical model supposing unique zones, as it is explained in section 5.5.2.

Once the results for the analytical model considering a unique zone are obtained, they are introduced with the trip request generation and tour planning procedure in VISUM.

6.3.1. Inputs

The inputs introduced in the procedures described in 8.2.1. and 8.2.2. and using the values resulting from the analytical model in the case of a unique zone, are:

- OD matrix with the number of trips between zones, calculated directly from the hourly demand density.
- Pre-booking time, defined as the headway

$$prebooking\ time = H_{sa} \tag{36}$$

- Maximum detour time, defined as the difference between the time consumed for the route if the vehicle is full, the number of requests is equal to the vehicle capacity (maximum detour), compared with the situation in which just one passenger goes in the vehicle, the number of requests is 1 (no detour)

$$maximum\ detour\ time = (r_{N_r=S_V}/v_c) - (r_{N_r=1}/v_c) \tag{37}$$

- Detour factor, equal to 5
- Always accepted detour time, equal to 0. Due to the structure of the equation 35 and the definition of maximum detour time and detour factor, makes no necessary to have a value for the always accepted detour time
- Time for boarding and alighting per trip request, equal to 15 seconds
- Time for boarding and alighting per passenger, equal to 2 seconds
- Number of vehicles, equal to the roundup value of the F obtained in the analytical model
- Number of seats per vehicle, equal to the roundup value of S_V obtained in the analytical model

According to the introduction of battery-electric vehicles, the node selected as charging area is the node selected as holding area (the node in the station) and two parameters should be introduced:

- The maximum range is set to 30km, as the consideration is with the scheme of opportunity charging, where the range, as the battery pack is smaller, is around 30 and 50km (Badia & Jenelius, 2020b).
- The charging duration is set to 3min, as the battery is estimated to have a capacity of 24 kWh (Chen, Kockelman, & Hanna, 2016) and the charging speed is 450 kWh/h, as the considered stations have fast charging (Badia & Jenelius, 2020b).

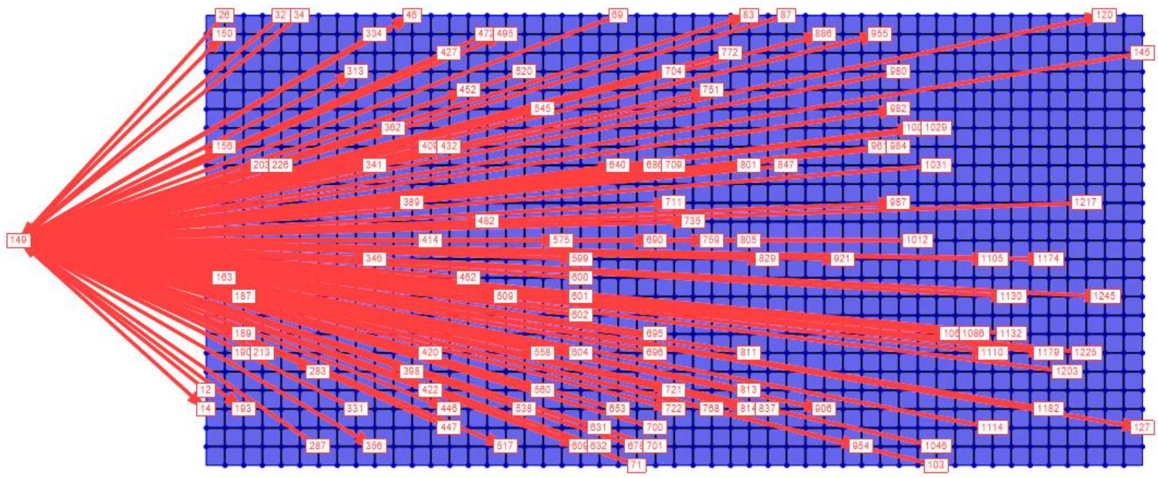


FIGURE 38. Trips requests generated for one hour for the case of δ=200 pax/km2-h

6.3.2. Outputs

The outputs needed for the calculation of the equation 4 for the agency costs and their obtention are:

- Travelled kilometres per hour of operation (K), obtained from the sum of km travelled in each path (by each vehicle)
- Fleet size per hour of operation (F) is an input
- Bus size or capacity (S_V) is an input

And for the user costs, from the equation 5:

- Access time (A) always has a value of 0
- Waiting time (W), obtained as:

$$W = OWT_{average} + prebooking\ time/2 = OWT_{average} + H_{sa}/2 \quad (38)$$

  OWT (origin wait time) is a skim matrix of time (for the ones in the OD matrix) that gives the wait time at the start stop point. (A skim typically refers to a matrix of impedance estimates between zones)
- Cruising time (R), given by the value in the skim matrix of time RIT (riding time) that gives the riding time between the departure from the origin stop point and the arrival at the destination stop point.
- Time at stops (S), obtained from information provided by the software and calculated with the equation:

$$S = time\ per\ stop \cdot stops\ per\ cycle \quad (39)$$

$$time\ per\ stop = (\sum time\ at\ stops)/n\ stops_{total} \quad (40)$$

$$stops\ per\ cycle = [(n\ stops_{total} - n\ stops_{holding\ area})/n\ stops_{holding\ area}] + 1 \quad (41)$$

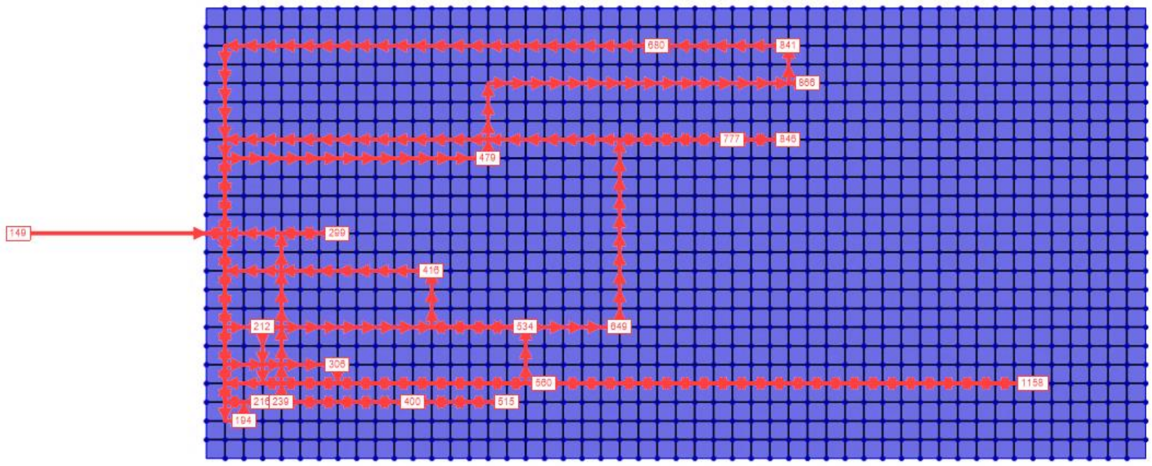


FIGURE 39. Path resultant from the dispatching procedure for one of the vehicles during one hour for the case of δ=200 pax/km2-h.

6.3.3. Results

With the introduction of the inputs described previously, the outputs can be compared with the results from the analytical model.

TABLE 29. Results obtained from the analytical model adapted for the unique subzone

δ (pax/km^2-h)	Z (€/pax-h)	C_A (€/pax-h)	C_U (€/pax-h)	S_V (pax)	K (km)	F (veh)	W (h)	R (h)	S (h)
10	2.74	0.94	1.80	3.50	54.76	2.06	0.0886	0.1065	0.0129
20	2.53	0.94	1.60	3.50	109.52	4.11	0.0691	0.1065	0.0129
30	2.45	0.90	1.56	3.75	155.94	5.88	0.0640	0.1083	0.0135
40	2.41	0.86	1.55	4.00	198.00	7.49	0.0616	0.1100	0.0142
50	2.44	1.01	1.43	3.13	298.22	11.14	0.0560	0.1035	0.0120
100	2.35	0.90	1.45	3.75	519.79	19.59	0.0542	0.1083	0.0135
150	2.34	0.90	1.44	3.74	782.05	29.46	0.0528	0.1082	0.0135
200	2.28	0.75	1.53	4.98	838.54	32.14	0.0546	0.1160	0.0166
250	2.30	0.84	1.46	4.15	1203.46	45.60	0.0525	0.1110	0.0145
500	2.26	0.70	1.56	5.53	1935.91	74.76	0.0538	0.1190	0.0180

TABLE 30. Results obtained from the simulation in VISUM

δ (pax/km^2-h)	Z (€/pax-h)	C_A (€/pax-h)	C_U (€/pax-h)	S_V (pax)	K (km)	F (veh)	W (h)	R (h)	S (h)
10	3.01	1.48	1.53	4	58.15	3	0.0756	0.0900	0.0109
20	2.49	1.19	1.30	4	102.23	5	0.0522	0.0911	0.0131
30	2.22	0.95	1.27	4	132.74	6	0.0453	0.0958	0.0142
40	2.17	0.93	1.24	4	174.56	8	0.0406	0.0978	0.0145
50	2.25	1.08	1.17	4	220.26	12	0.0346	0.0975	0.0143
100	2.10	0.90	1.20	4	390.01	20	0.0360	0.0972	0.0163
150	2.11	0.89	1.22	4	565.55	30	0.0383	0.0961	0.0171
200	2.12	0.76	1.36	5	800.78	33	0.0530	0.0958	0.0147
250	2.13	0.84	1.29	5	997.33	46	0.0450	0.0983	0.0147
500	2.19	0.71	1.48	6	1849.19	75	0.0638	0.0944	0.0168

TABLE 31. Correlation coefficient results for the results in Table 29 and 30

Z	C_A	C_U	S_V	K	F	W	R	S
0.9271	0.7174	0.8081	0.9116	0.9932	0.9999	0.6728	0.1048	0.4492

The results shown in Tables 29 and 30, represented in Figure 40, are clearly correlated, as shown in Table 31, with values for the coefficient of correlation that makes the value of the simulation valid for the assumption that the analytical model represents well enough the behaviour of the DRT service in a real case. The only exception is with the R but that does not affect to the final results of the costs. The value of R is smaller in the simulation as the analytical model estimates the length of the route using approximation formulas (formulated in Appendix A in (Badia & Jenelius, 2020a and 2020b) from (Daganzo, 1984) and (Quadrifoglio & Li, 2009)) that considers bands in which there is a go and return until the end of the zone. That is not necessary in some of the cases, and it will depend on the different trip requests generated for being served. The R obtained from the simulation is smaller as it adapts more to an optimum that is more adjusted to the reality, being an example of it the figure 39.

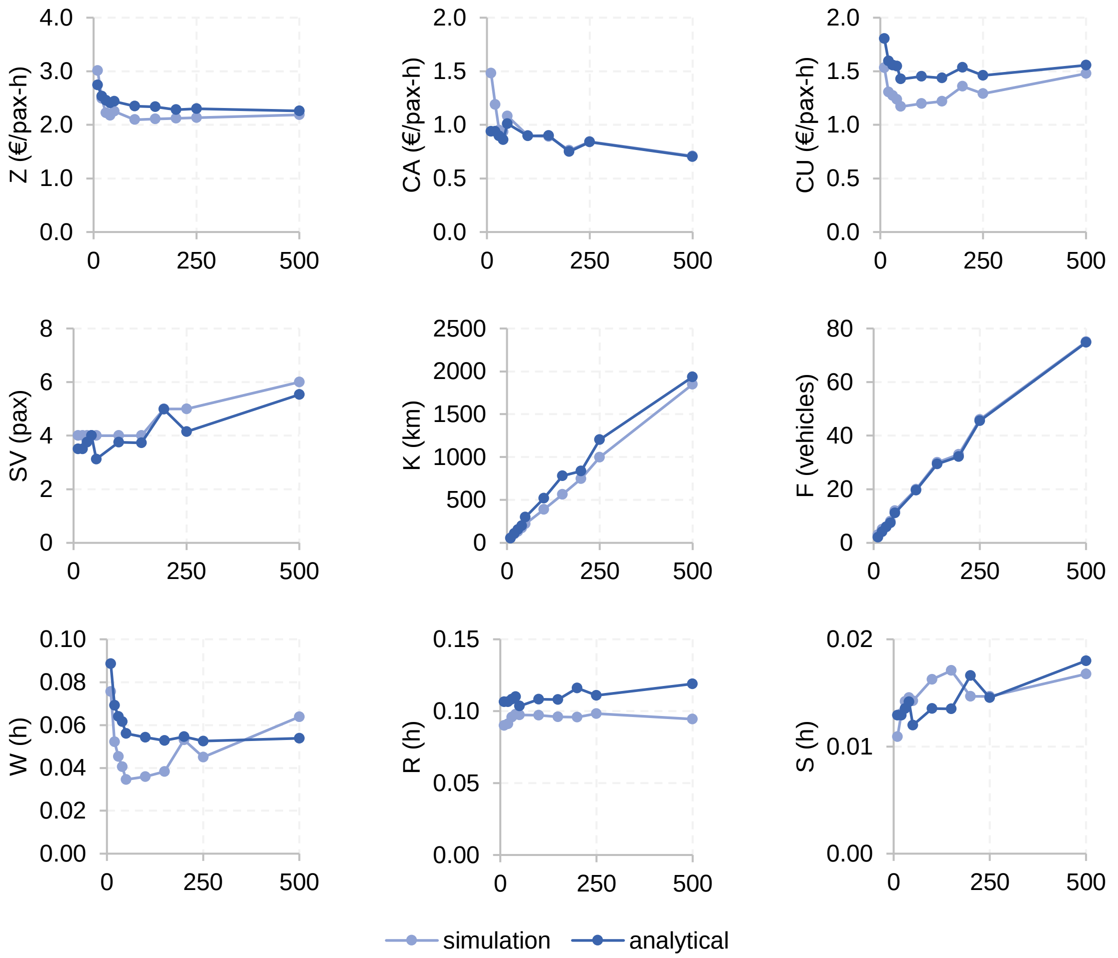


FIGURE 40. Comparison of the results for the different values of hourly demand density for the simulation and the analytical model, for the idealised case presented

6.4. Simulation of the suitable areas

The simulation of the suitable areas to implement DRT as shown in Section 4.3 is conducted to evaluate the results given by the software and compare it with the ones of the analytical model. With the results of the validation for the simplified case performed previously, it is assumed that, although with changes due to the application in a realistic scheme, the results obtained in VISUM are in concordance with the results of the analytical model when the purpose is to analyse the different operating strategies.

The Trip requests generation and tour planning procedures gives the results shown in Figures 41 and 42, respectively. The results are depicted for one of the 34 zones evaluated.

As it has been explained previously in this section and due to the stochastic disaggregation of the trip requests, the results are obtained after multiple calculations of the tour planning procedure, considering various seed random number for trip request generation.

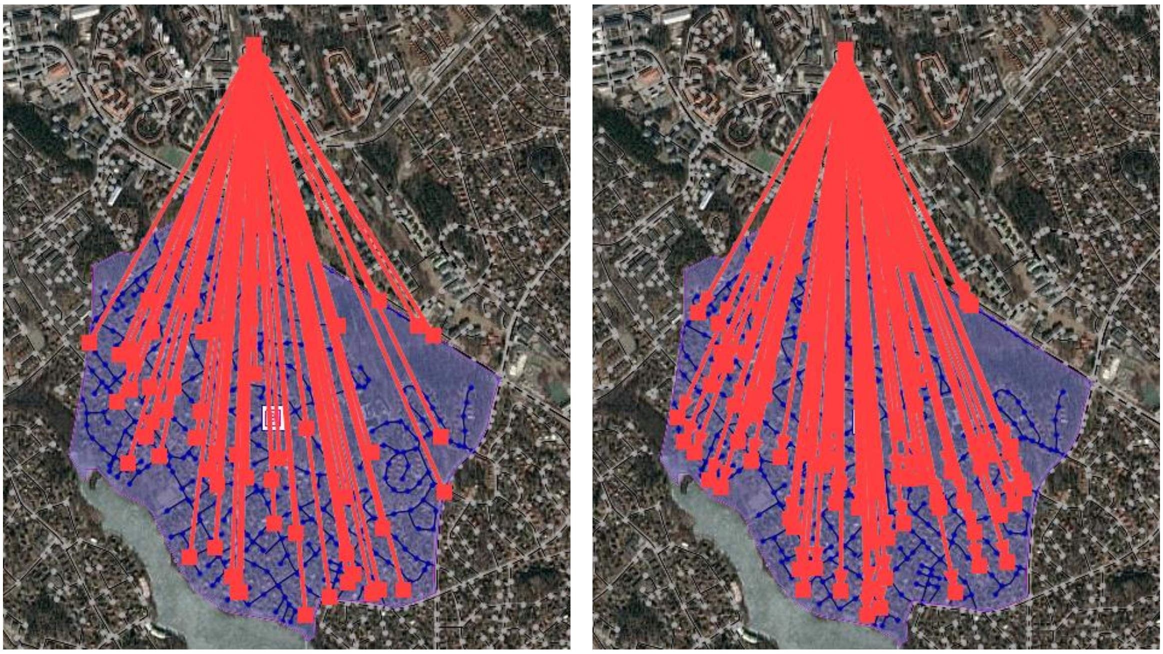


FIGURE 41. Trips generated from zone to station (left) and vice versa (right) for one hour

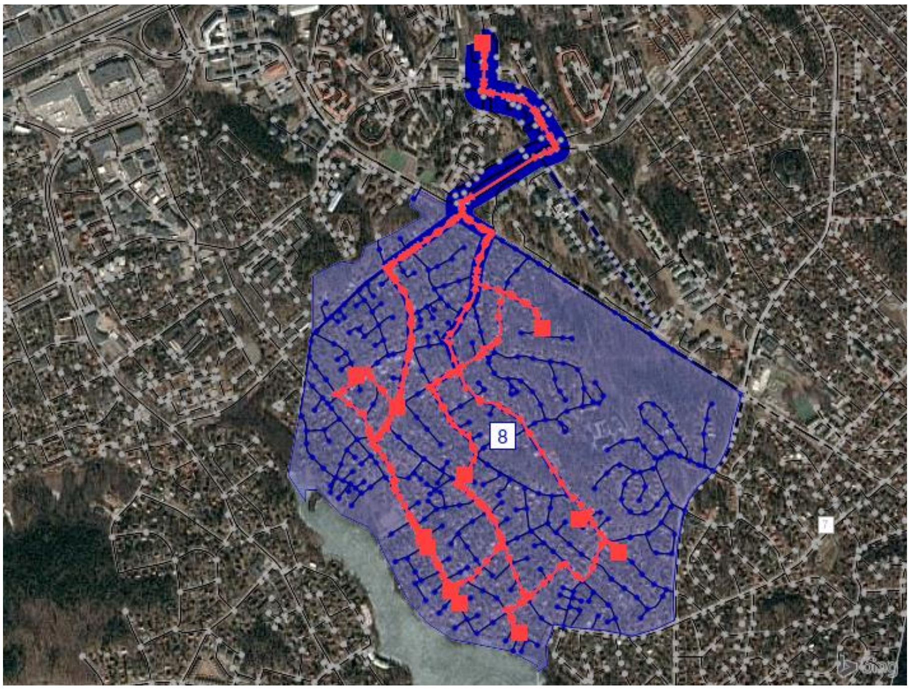


FIGURE 42. Path resultant from the dispatching procedure for one vehicle for one hour

Before comparing the results from the simulation, the results given in Table 27 should be corrected for this purpose, as the fleet size and the capacity of the vehicle in the optimization are not a round number and VISUM needs for those values rounded numbers, as it is representative of the reality. The results from the analytical model for both strategies considered should be repeated with the rounded values, what increases the values compared with respect to the values obtained in Section 5.

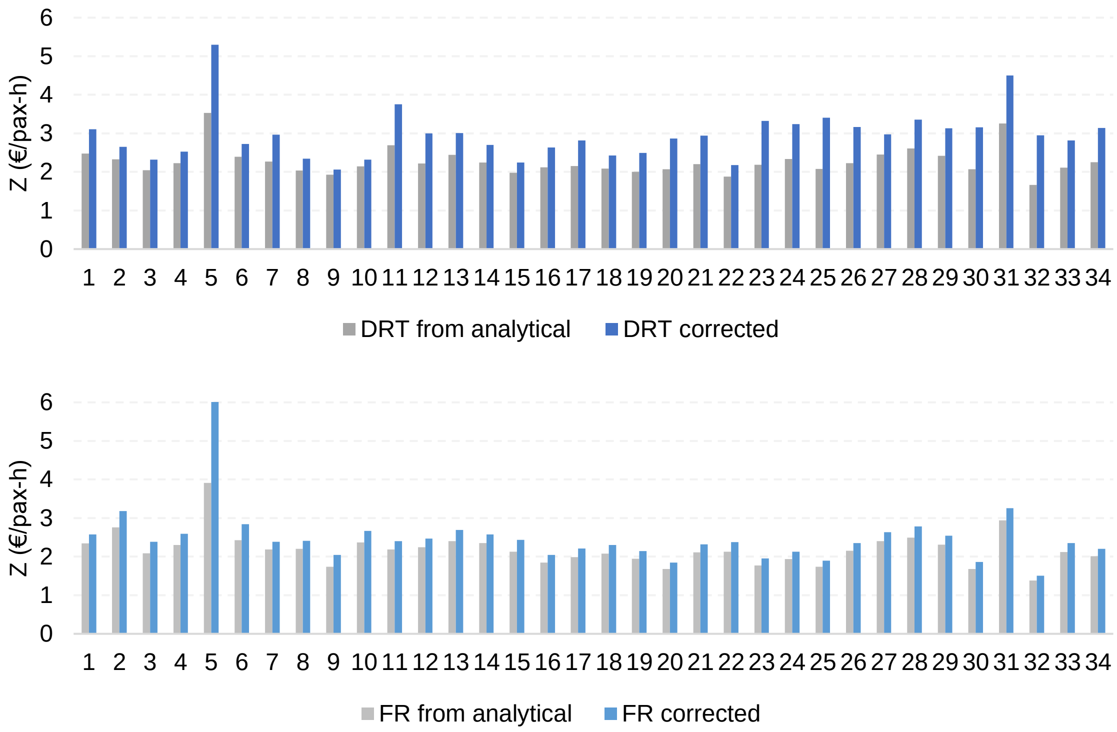


FIGURE 43. Results of the system total costs after correcting results with rounded values

As it is shown in Figure 43, the corrected values are higher than the initial ones, with a bigger or lesser difference dependent on the difference between the original value obtained and the rounded-up value of the fleet size and vehicle capacity.

6.5. Results

With the results of the validation for the simplified case performed previously, it is assumed that, although with changes due to the application in a realistic scheme, the results obtained in VISUM are in concordance with the results of the analytical model when the purpose is to analyse the different operating strategies.

With the evaluation of the results from the VISUM analysis it is possible to assess the influence of the real shape of the areas as well as considering the real pattern of streets and conclude if the analytical model is able to give representative values for non-simplified zones.

TABLE 32. Results for the final stage of automation and electrification considered and the two operating strategies for each zone and selection of the optimal operating strategy

	FR service (AV_F)	**DRT service** (AV_F)		**optimal operating strategy**	
id	**analytical corrected**	**analytical corrected**	**simulation VISUM**	$FR_{analytical}$ **and** $DRT_{analytical}$	$FR_{analytical}$ **and** $DRT_{simulation}$
1	2.58	3.11	2.47	FR	DRT
2	3.18	2.65	2.48	DRT	DRT
3	2.39	2.32	1.99	DRT	DRT
4	2.59	2.53	2.21	DRT	DRT
5	6.02	5.30	5.13	DRT	DRT
6	2.84	2.73	2.60	DRT	DRT

7	2.39	2.97	2.34	FR	DRT
8	2.41	2.35	2.10	DRT	DRT
9	2.04	2.06	2.06	FR	FR
10	2.67	2.32	2.25	DRT	DRT
11	2.40	3.76	2.81	FR	FR
12	2.47	3.00	2.30	FR	DRT
13	2.69	3.01	2.21	FR	DRT
14	2.58	2.70	2.16	FR	DRT
15	2.43	2.24	1.97	DRT	DRT
16	2.04	2.64	2.46	FR	FR
17	2.21	2.82	2.21	FR	DRT
18	2.30	2.43	2.03	FR	DRT
19	2.15	2.50	2.09	FR	DRT
20	1.84	2.87	2.05	FR	FR
21	2.32	2.94	2.15	FR	DRT
22	2.38	2.18	2.09	DRT	DRT
23	1.95	3.33	2.36	FR	FR
24	2.13	3.24	2.27	FR	FR
25	1.90	3.41	2.59	FR	FR
26	2.36	3.16	2.69	FR	FR
27	2.64	2.98	2.66	FR	FR
28	2.79	3.35	2.71	FR	DRT
29	2.54	3.14	2.29	FR	DRT
30	1.87	3.15	2.49	FR	FR
31	3.25	4.50	3.02	FR	DRT
32	1.51	2.95	2.45	FR	FR
33	2.35	2.81	2.27	FR	DRT
34	2.20	3.14	2.66	FR	FR

When comparing the results from the FR strategy to the DRT ones in the case of using the simulation, 22 zones out of 34 result having the DRT as the optimal operation service, what contrasts with the result obtained in Section 5, where it was 12 the number of zones with the DRT as the cheaper strategy in the stage 3 (AV_F).

As Table 32 depicts, the values for the DRT simulation are smaller than the ones obtained in the analytical model, what can be explained because the simulation optimized better the routes and also takes the real shape of the areas and the real street pattern within the area and between the area and the station. In Figure 44 it is shown that the bigger the route factor is for a zone; the greater will be the reduction of costs between analytical and simulation. The rest of parameters shown in Table 26 that characterize the areas do not show any correlation with the difference between the costs.

The results depicted in Figure 44 can be explained because the route factor calculated in Section 5.7 is considering the complete areas while, with the capacity of the vehicles, the vehicle goes through a route within a small portion of the complete scope of the area, as it can be seen in Figure 42. The mentioned fact makes the route factor to not have a great impact as it firstly seemed and the areas with bigger values of route factor would have their total system costs overestimated.

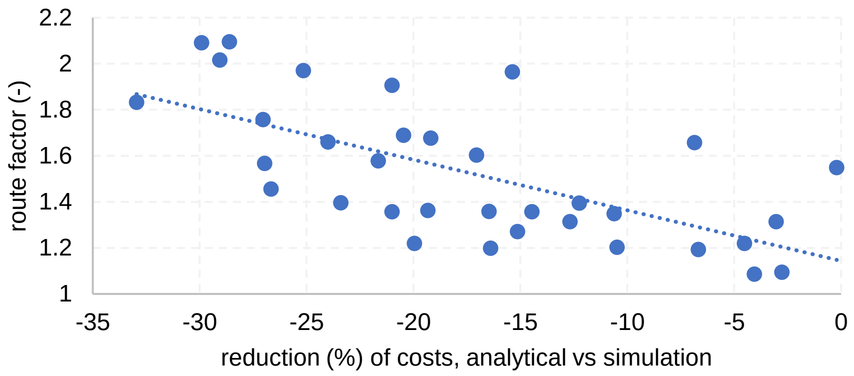


FIGURE 44. Variation of the reduction of costs in relation with the route factor

After the consideration of the simulation values for comparing them with the analytical values, there are some changes according to the lower boundaries. All the zones in which the DRT is the optimal operating system for the final stage have a hourly demand density with values smaller than 180pax/km^2-h, values of time higher than 7.50€/h and values for the route factor smaller than 1.80.

7. Conclusion

There are several conclusions that can be highlighted in this section, as well as a discussion of the future work that can be achieved in order to complete this project. This conclusion tries to answer the research questions laid out in the first chapter of this document.

First of all, the development of the automation and electrification technologies in vehicles will lead to a new state in which new forms of mobility will be feasible to implement, both in technologically but also economically. Even in that state, the applicability of a demand responsive transport as a feeder for first/last mile system is restricted to certain circumstances around the rail corridors according to urban configuration and access to transit as well as socioeconomical conditions. Under that conditions mentioned, 34 suburban areas has been identified around the different rail corridors in the Stockholm county in which it would be possible to implement a DRT service in order to improve the existing public transport, where there is a lack of a good first/last mile service, being all these zones selected out of the inner city of Stockholm and mainly located around satellite cities in the suburban area.

Additionally, the comparison between different operating strategies is performed for each one of the different stages of technology development considered. In the current situation, the high operation costs limit the applicability of on-demand services while in the future, with the costs reduction thanks to the technology improvements mentioned, it will be possible to extent this kind of service, substituting in some cases fixed-route services, giving a better service to the users. It is corroborated with the results that, from a total of 34 zones studied, 1 zone is cheaper in the conventional (0) stage with DRT than FR, 0 zones in the current (1) stage, 4 zones in the intermediate (2) stage and finally 12 zones in the final (3) stage. In the final stage, the comparison of these costs obtained comparing the DRT or FR strategies gives some upper limits of applicability of DRT as the optimal strategy, having in all the cases the hourly demand density values smaller than 140pax/km^2-h, values of time higher than 7.50€/h and values for the route factor smaller than 1.40. What has been mentioned implies that the applicability of DRT as the optimal strategy in a future stage of automation and electrification will be feasible in areas with low demand density, normally residential low density areas, a value of time higher than the average, what implies a household medium income higher than the average, and street patterns with a good connectivity, what implies that they are more similar to an infinitely dense grid.

The simulation with VISUM, although includes a smaller scope of what was initially planned, shows some conclusions to be analysed. Firstly, with the consideration of an idealised model, the correlation between the results permit to assume that the DRT service is well represented by the analytical model. In the case of the simulation under realistic cases, what means the simulation of the 34 areas considered, the results shows that, for the final (3) stage, the number of zones in which the DRT would be the optimal operation strategy is 22, as the system total costs reduces their values in the simulation in comparison with the analytical model due to a better and more realistic optimization of the routes done by the vehicles in comparison with the approximations done in the analytical.

7.1. Future work

Although the results obtained are a good basis to build upon, it is not sufficient. The conclusions according to the simulation clearly shows that the analytical model leave room for improvement to adapt it to realistic applications, although it is a good indicator with no use of a specific software.

Improvements should be done in the consideration of the route factor values, as it has been shown that in some cases its value is overestimated.

As it has been also mentioned in the document, the initial plan of evaluation of the DRT service in combination with public transport has not been finally done, due to the lack of time and complications during the realisation of the project. As the automated vehicles will allow public transport systems to supply a more attractive service, the simulation of the mentioned combination would be desirable in future works not just as a modelling of simplified cases but also as an application to real cases.

The changes in urban mobility is introducing new modes of transport that can be a good solution for first/last mile as the cases studied for the implementation of DRT. The addition of some micro-mobility options could be studied.

In conclusion, the field of the implementation of automated vehicles and its implementation as a feeder solution in first/last mile will increase its applicability in the coming ages, and there is many work to be done in the future according to it and to upcoming solutions in the ambit of the new mobility.

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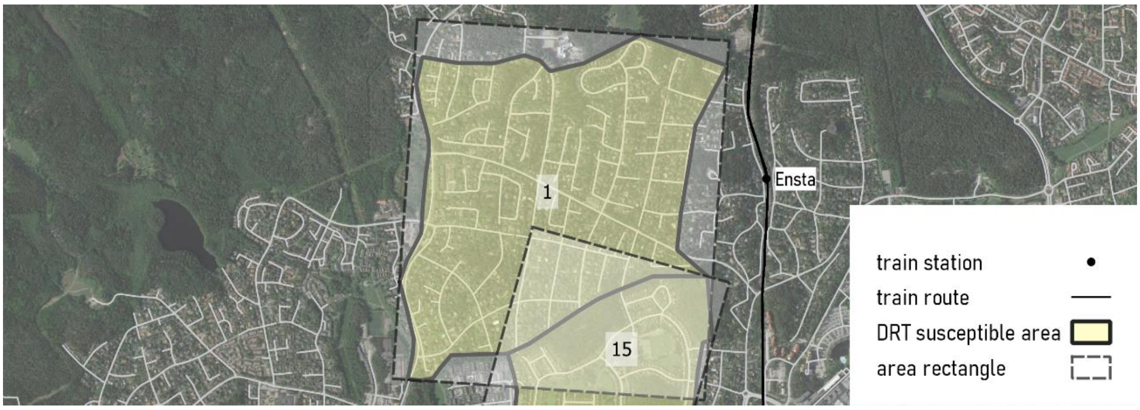
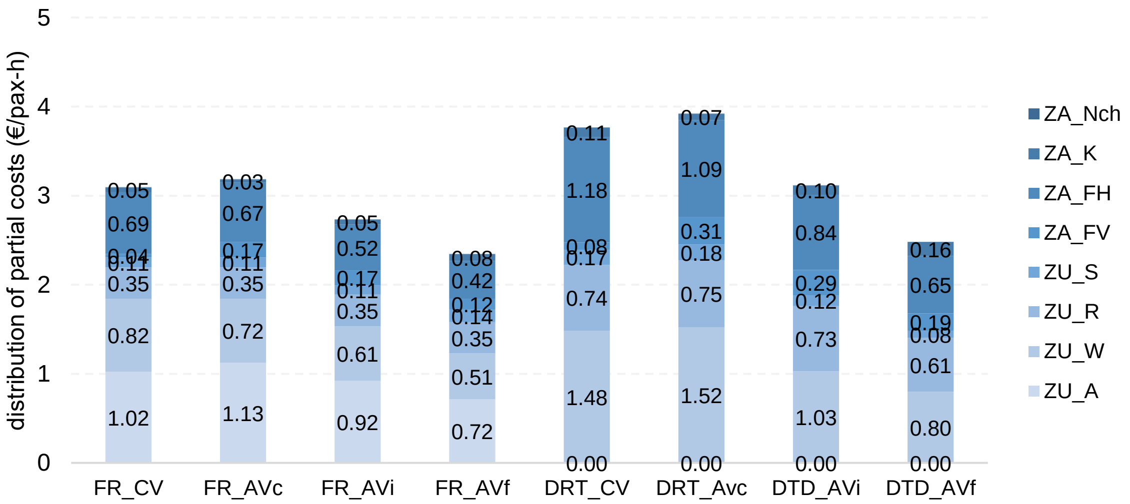
APPENDIX A. DRT implementation suitable areas

ZONE 1. Ensta - Ella

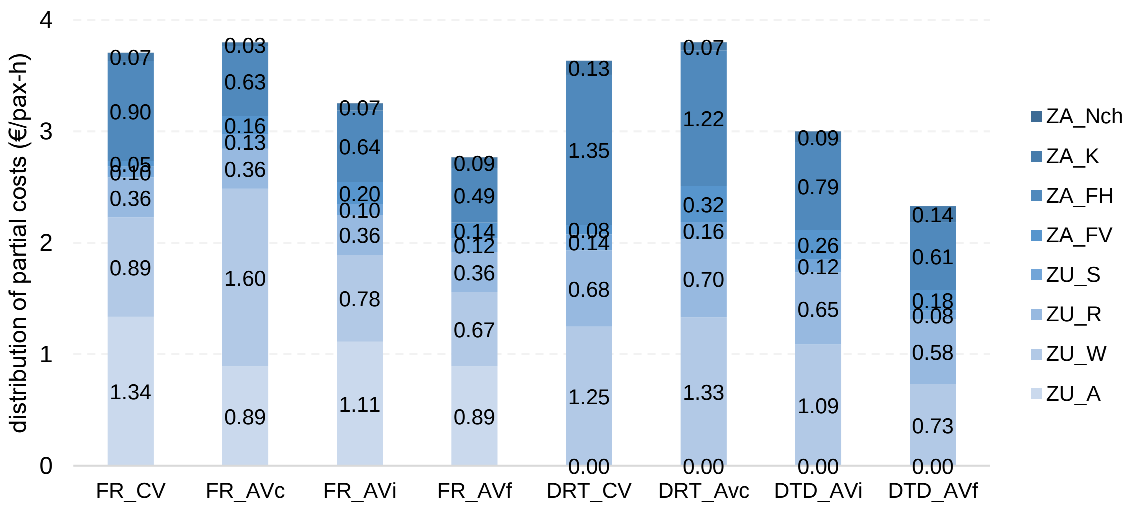


var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	367.47
D_L	*(km)*	longitudinal dimension	1.30
D_W	*(km)*	transversal dimension	1.22
	(km²)	area	1.59
γ_r	-	route factor	1.6883
	(SEK/year)	household medium income	424797.84
VoT	*(€/h)*	value of time	8.19
	(pax/km²-day)	daily demand density	1132.86
	(pax/km²-h)	peak hour demand density	139.94
δ	*(pax/km²-h)*	hourly demand density	75.52
	(pax/h)	hourly trips	119.77

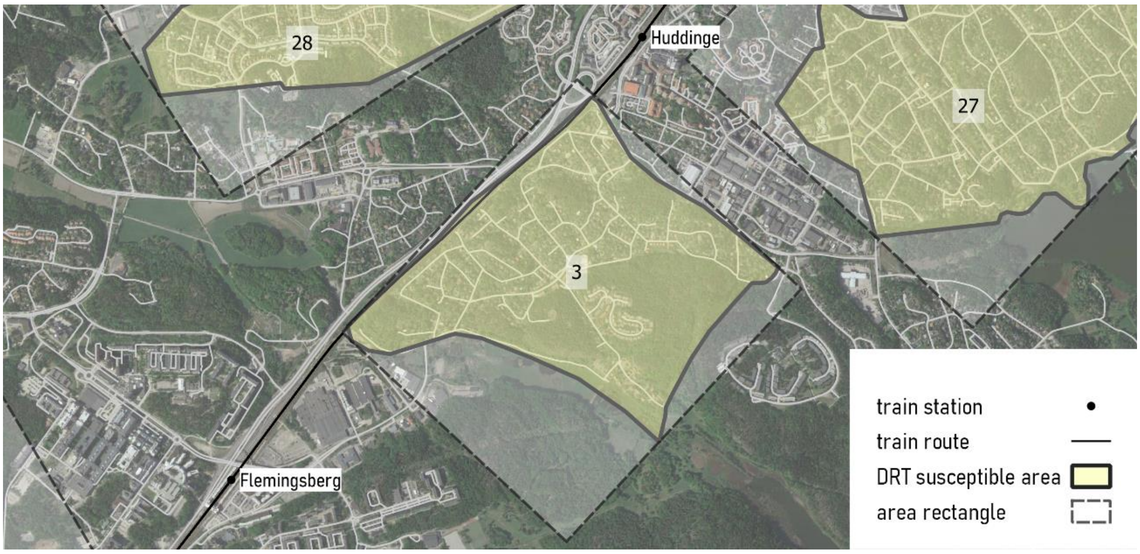


ZONE 2. Viggbyholm

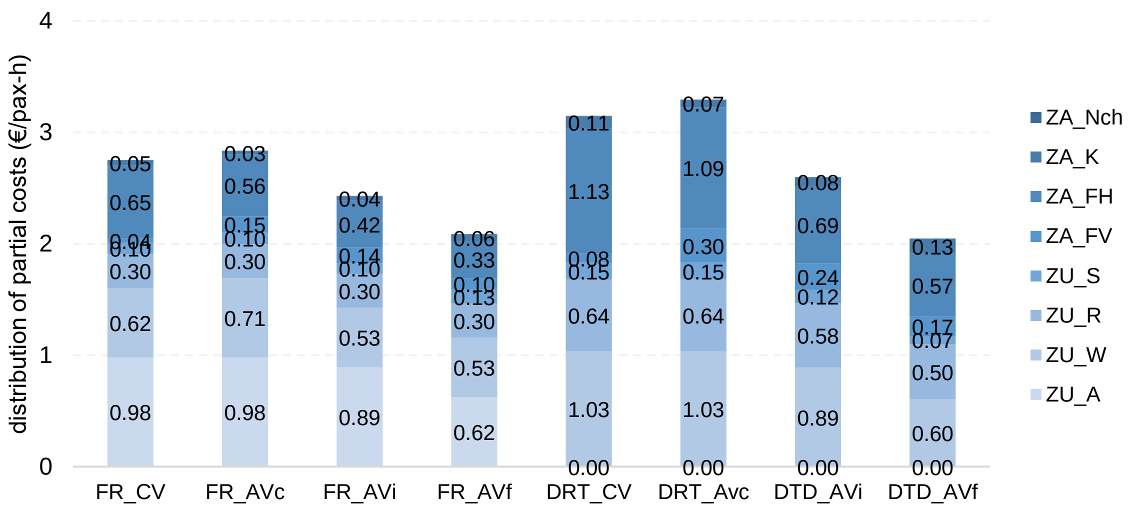
var	unit	input parameter	value
D_R	*(km)*	road length area to station	507.39
D_L	*(km)*	longitudinal dimension	0.95
D_W	*(km)*	transversal dimension	0.97
	(km^2)	area	0.92
$\boldsymbol{\gamma_r}$	-	route factor	1.193
	(SEK/year)	household medium income	461961.60
VoT	*(€/h)*	value of time	8.90
	(pax/km^2-day)	daily demand density	751.44
	(pax/km^2-h)	peak hour demand density	93.61
$\boldsymbol{\delta}$	*(pax/km^2-h)*	hourly demand density	50.10
	(pax/h)	hourly trips	46.02



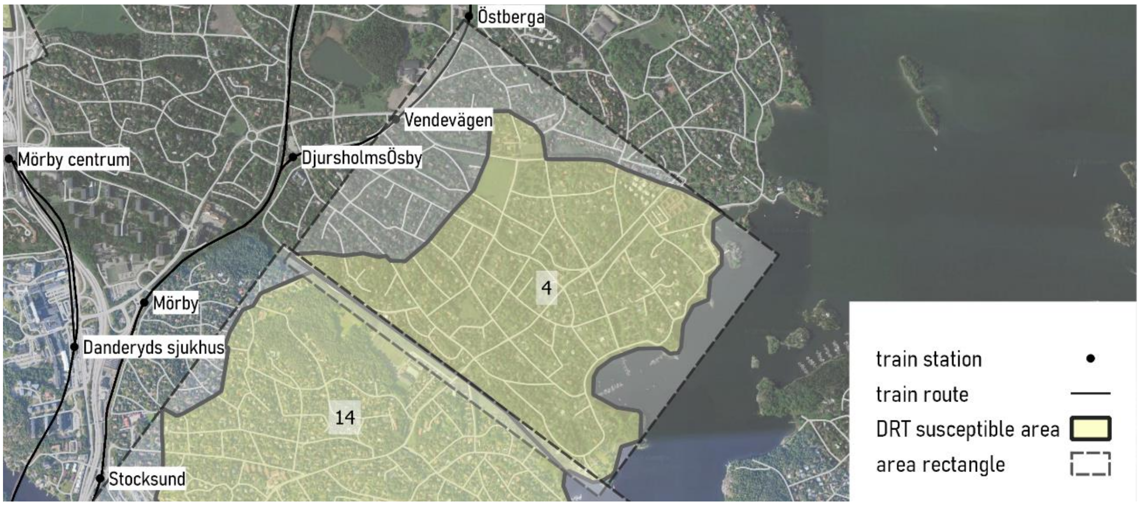
ZONE 3. Huddinge - Solgård



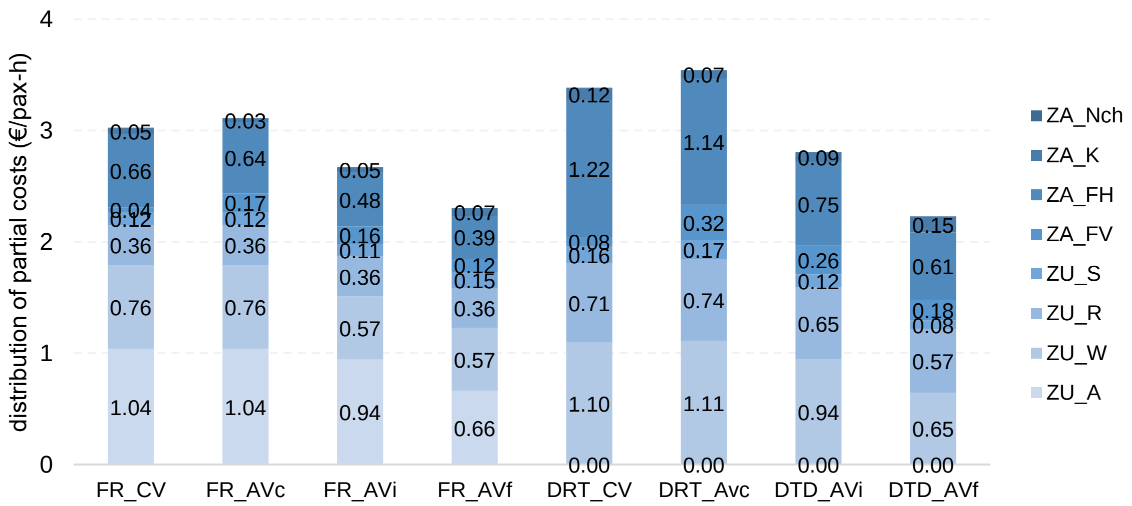
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	366.62
D_L	*(km)*	longitudinal dimension	1.42
D_W	*(km)*	transversal dimension	0.99
	(km²)	area	1.41
γ_r	-	route factor	1.3568
	(SEK/year)	household medium income	369895.30
VoT	*(€/h)*	value of time	7.13
	(pax/km²-day)	daily demand density	1156.37
	(pax/km²-h)	peak hour demand density	151.21
δ	*(pax/km²-h)*	hourly demand density	77.09
	(pax/h)	hourly trips	108.63



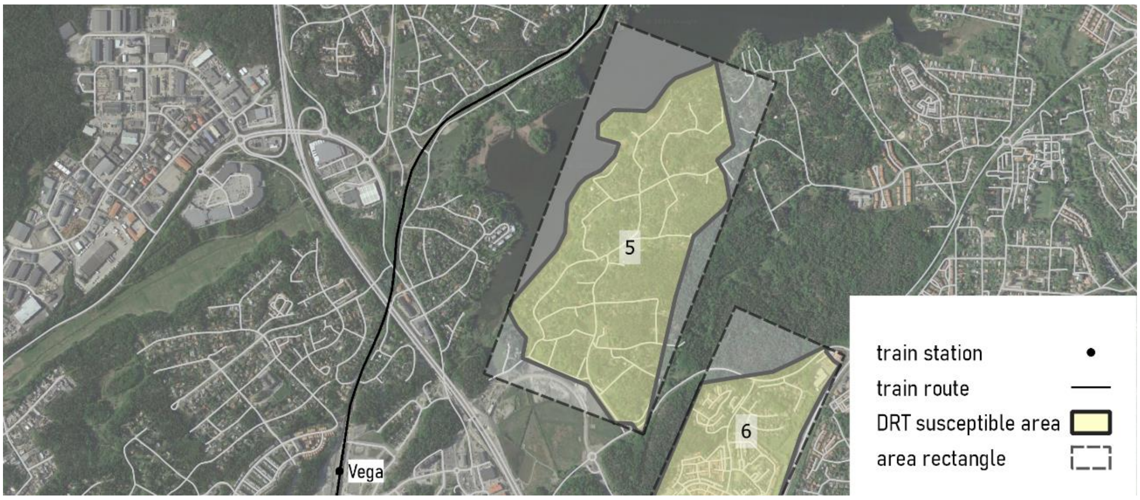
ZONE 4. Södra Djursholm



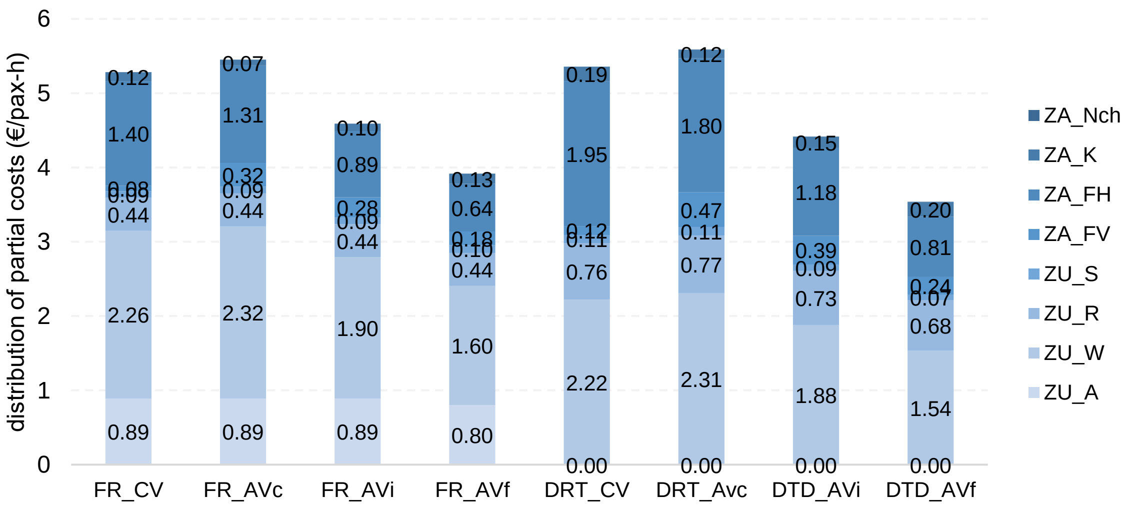
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	438.81
D_L	*(km)*	longitudinal dimension	1.60
D_W	*(km)*	transversal dimension	0.96
	(km²)	area	1.53
γ_r	-	route factor	1.314
	(SEK/year)	household medium income	391891.97
VoT	*(€/h)*	value of time	7.55
	(pax/km²-day)	daily demand density	992.31
	(pax/km²-h)	peak hour demand density	121.03
δ	*(pax/km²-h)*	hourly demand density	66.15
	(pax/h)	hourly trips	101.50



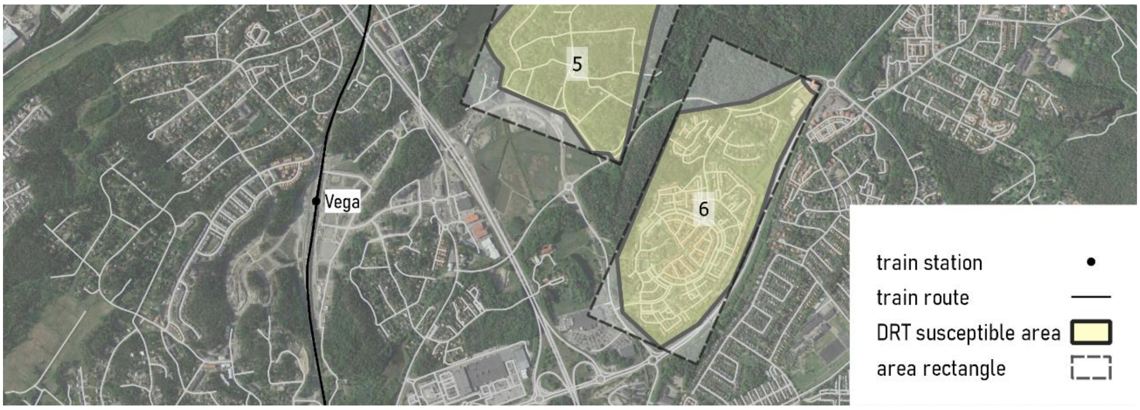
ZONE 5. Vega - Norrby



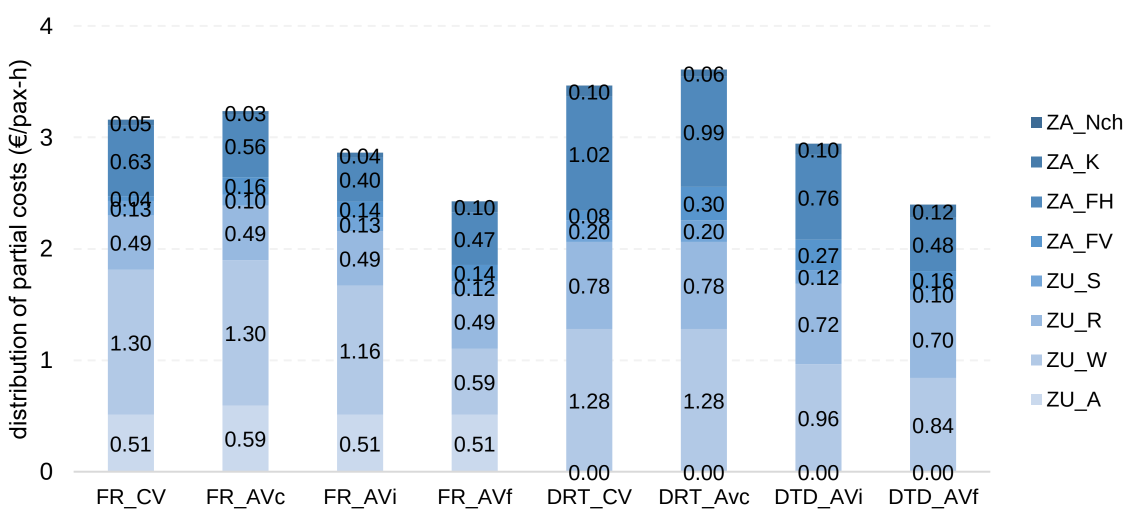
var	unit	input parameter	value
D_R	*(km)*	road length area to station	1007.57
D_L	*(km)*	longitudinal dimension	1.57
D_W	*(km)*	transversal dimension	0.57
	(km²)	area	0.90
γ_r	-	route factor	1.314
	(SEK/year)	household medium income	369909.63
VoT	*(€/h)*	value of time	7.13
	(pax/km²-day)	daily demand density	101.41
	(pax/km²-h)	peak hour demand density	12.14
δ	*(pax/km²-h)*	hourly demand density	6.76
	(pax/h)	hourly trips	6.08



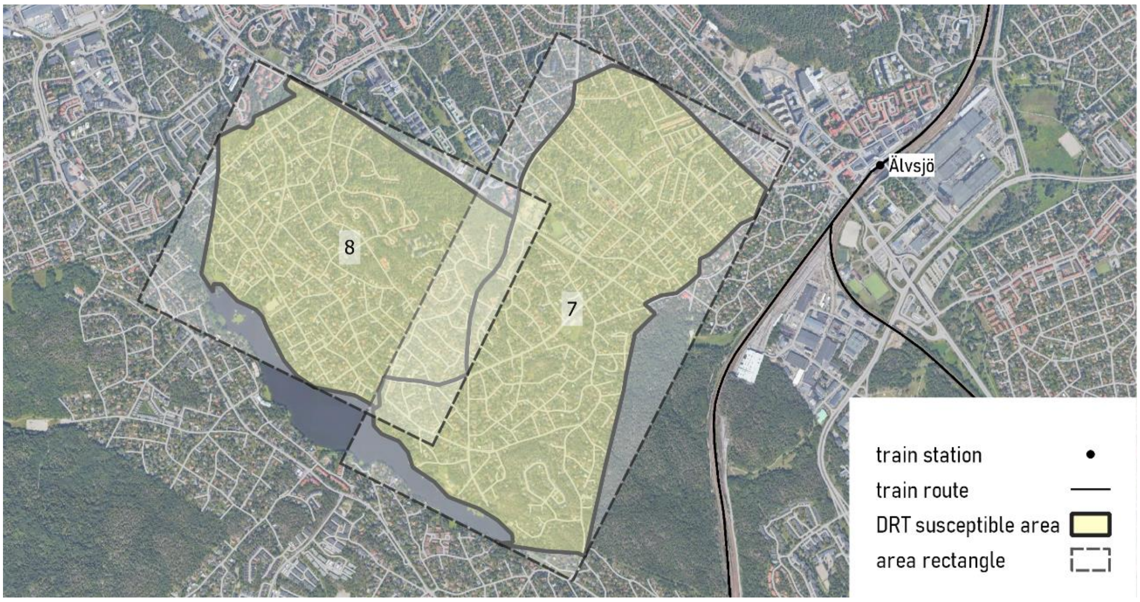
ZONE 6. Vega - Söderby



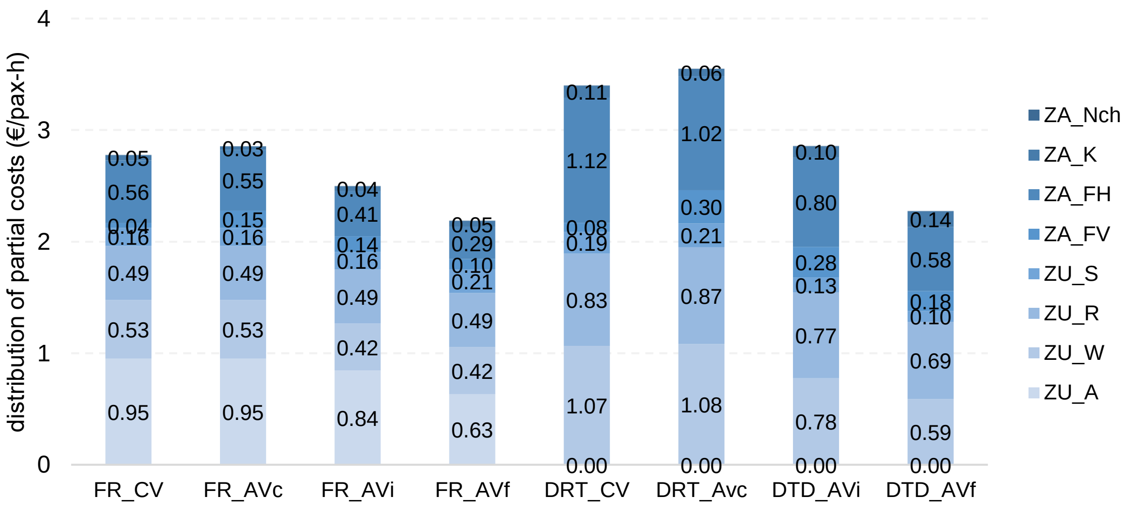
var	unit	input parameter	value
D_R	*(km)*	road length area to station	1420.63
D_L	*(km)*	longitudinal dimension	1.31
D_W	*(km)*	transversal dimension	0.45
	(km²)	area	0.59
γ_r	-	route factor	1.219
	(SEK/year)	household medium income	352643.71
VoT	*(€/h)*	value of time	6.80
	(pax/km²-day)	daily demand density	1162.17
	(pax/km²-h)	peak hour demand density	137.73
δ	*(pax/km²-h)*	hourly demand density	77.48
	(pax/h)	hourly trips	45.53



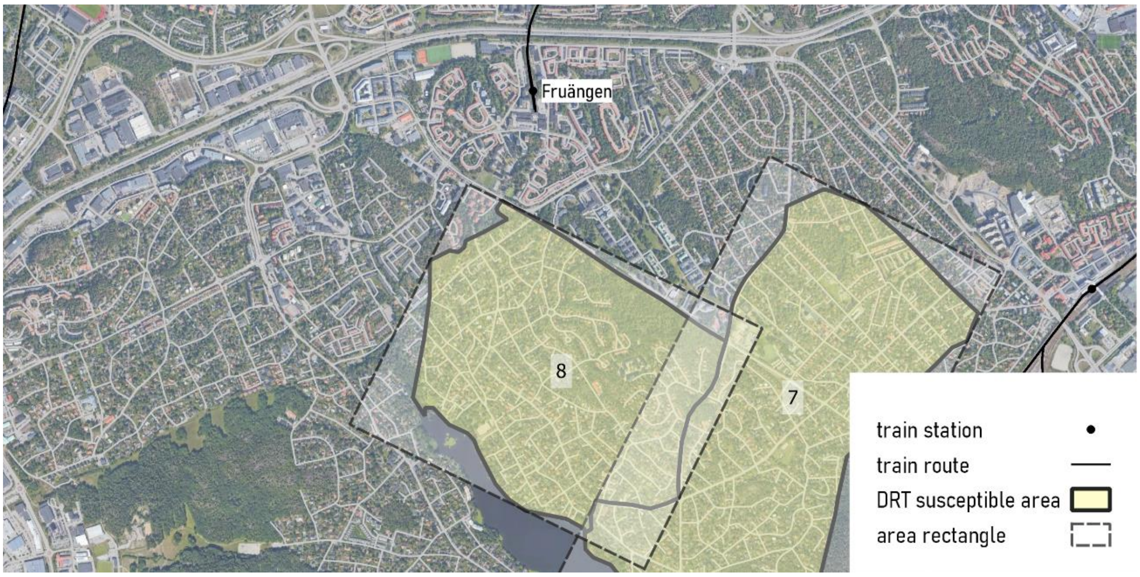
ZONE 7. Långsjö



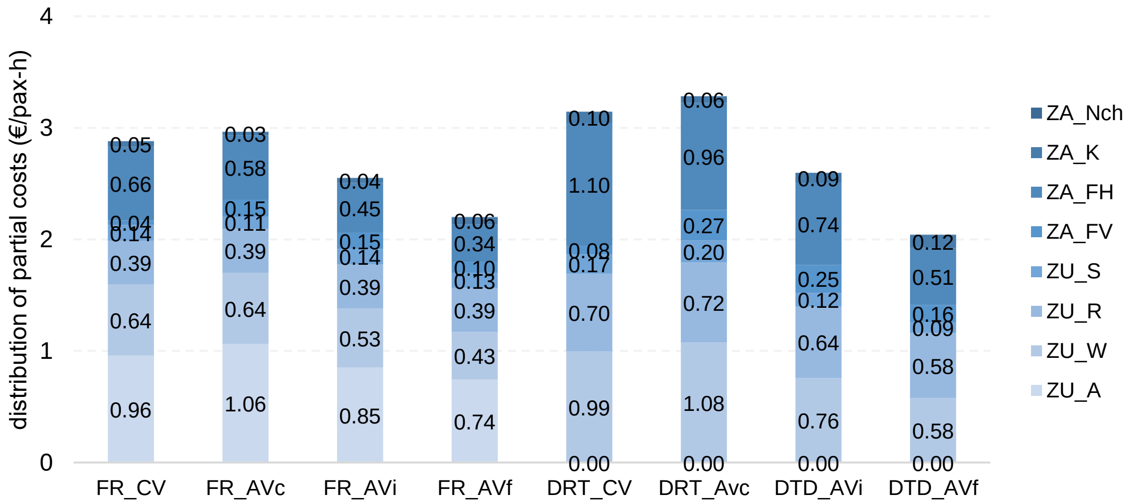
var	unit	input parameter	value
D_R	*(km)*	road length area to station	553.90
D_L	*(km)*	longitudinal dimension	2.03
D_W	*(km)*	transversal dimension	0.91
	(km^2)	area	1.84
γ_r	-	route factor	1.356
	(SEK/year)	household medium income	437903.05
VoT	*(€/h)*	value of time	8.44
	(pax/km^2-day)	daily demand density	2433.65
	(pax/km^2-h)	peak hour demand density	296.04
δ	*(pax/km^2-h)*	hourly demand density	162.24
	(pax/h)	hourly trips	298.95



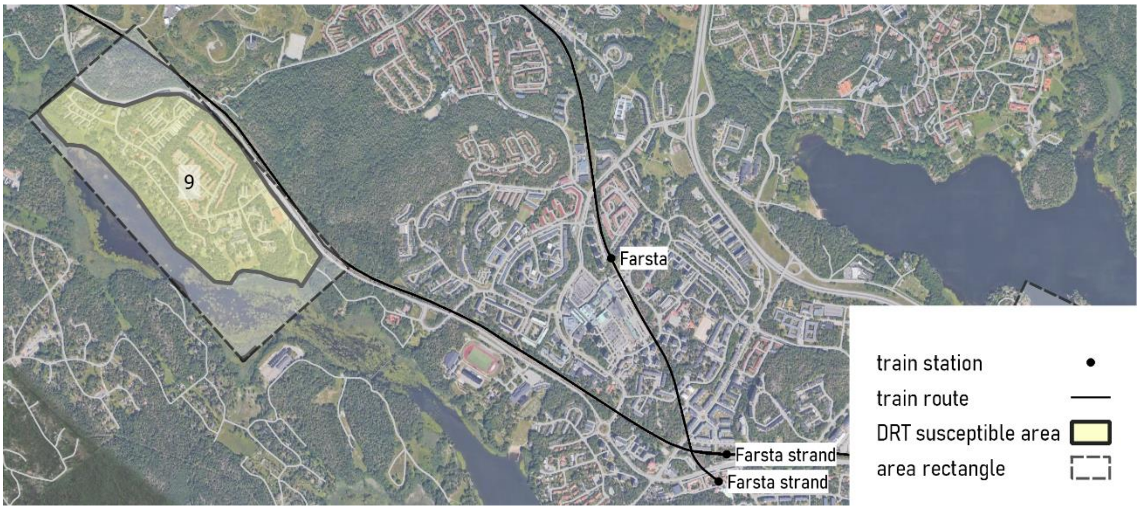
ZONE 8. Herrängen



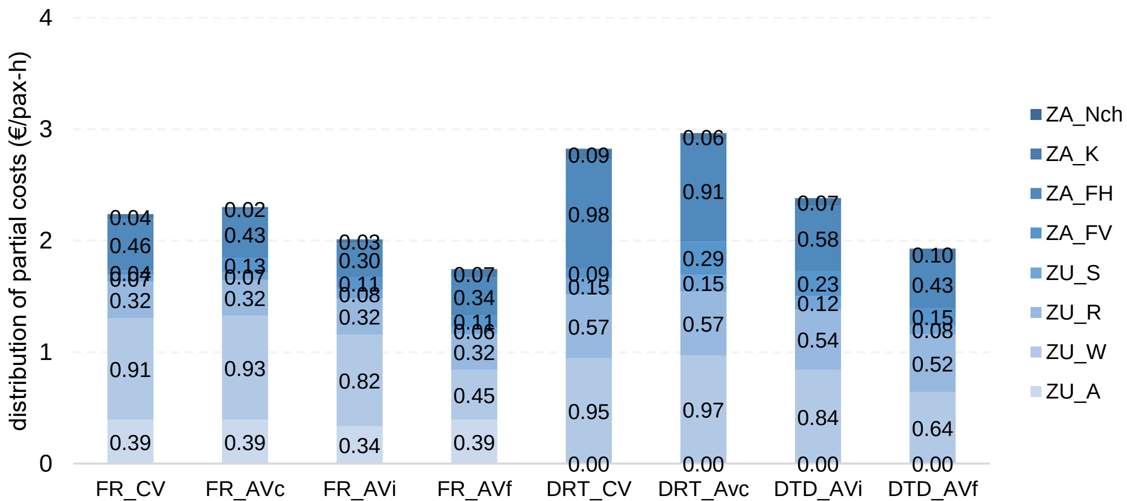
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	538.78
D_L	*(km)*	longitudinal dimension	1.14
D_W	*(km)*	transversal dimension	1.19
	(km^2)	area	1.37
γ_r	-	route factor	8.50
	(SEK/year)	household medium income	441068.43
VoT	*(€/h)*	value of time	9.386
	(pax/km^2-day)	daily demand density	1959.69
	(pax/km^2-h)	peak hour demand density	237.48
δ	*(pax/km^2-h)*	hourly demand density	130.65
	(pax/h)	hourly trips	178.52



ZONE 9. Havsörnstorget

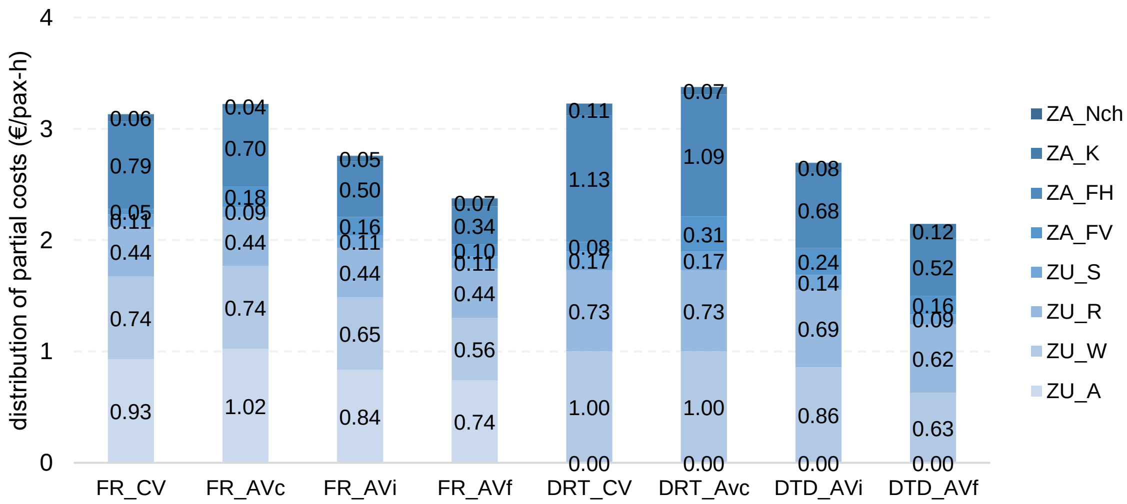


var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	1475.72
D_L	*(km)*	longitudinal dimension	1.31
D_W	*(km)*	transversal dimension	0.43
	(km^2)	area	0.57
γ_r	-	route factor	1.55
	(SEK/year)	household medium income	232628.46
VoT	*(€/h)*	value of time	4.48
	(pax/km^2-day)	daily demand density	1380.55
	(pax/km^2-h)	peak hour demand density	169.39
δ	*(pax/km^2-h)*	hourly demand density	92.04
	(pax/h)	hourly trips	52.21

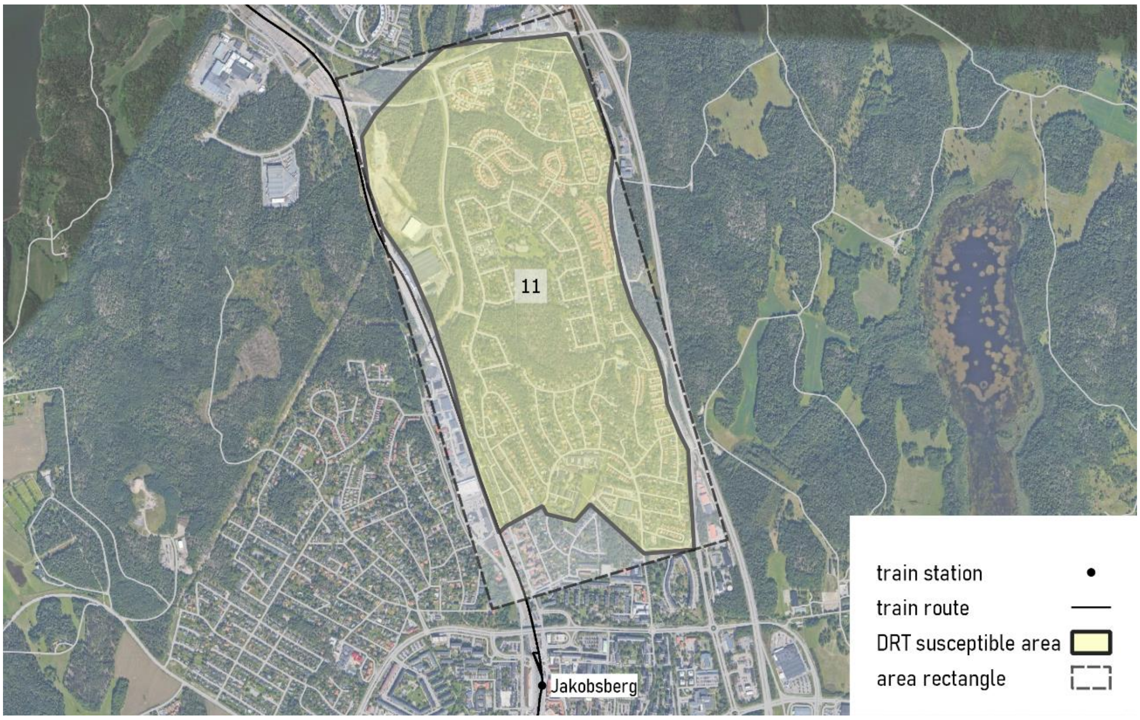


ZONE 10. Ormbacka - Skälby gård

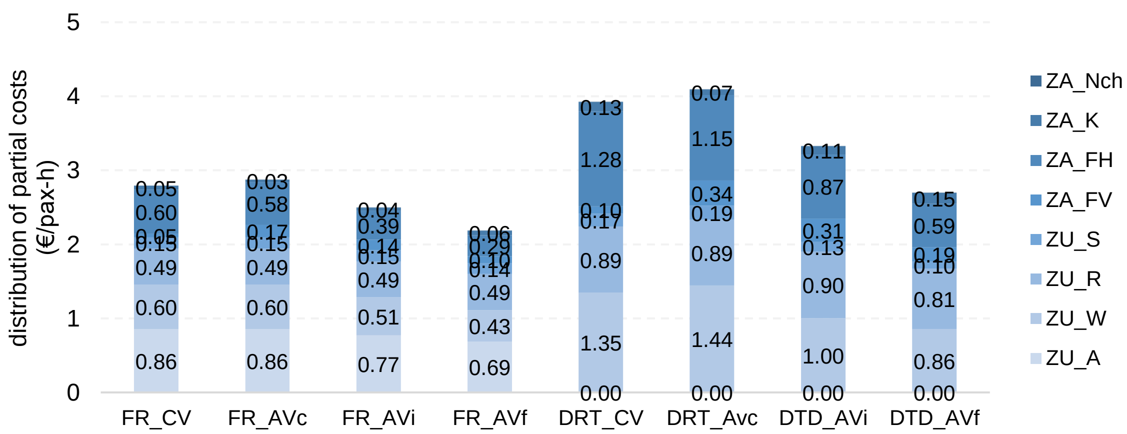
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	1055.75
D_L	*(km)*	longitudinal dimension	0.96
D_W	*(km)*	transversal dimension	1.07
	(km²)	area	1.02
γ_r	-	route factor	1.0937
	(SEK/year)	household medium income	385952.28
VoT	*(€/h)*	value of time	7.44
	(pax/km²-day)	daily demand density	1340.53
	(pax/km²-h)	peak hour demand density	165.31
δ	*(pax/km²-h)*	hourly demand density	89.37
	(pax/h)	hourly trips	91.22



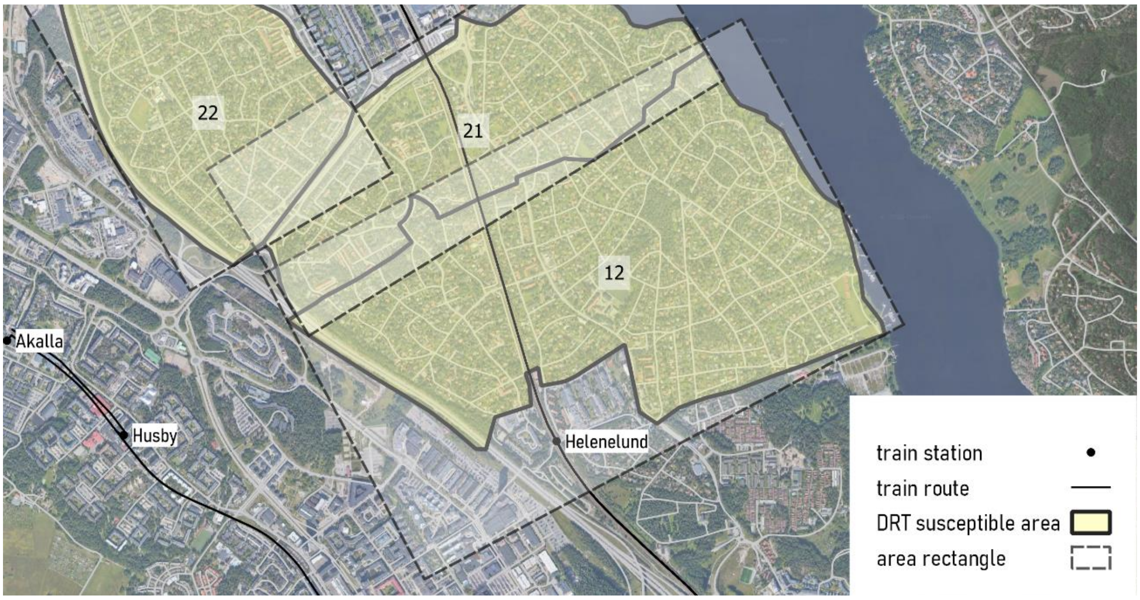
ZONE 11. Jakobsberg - Berghem



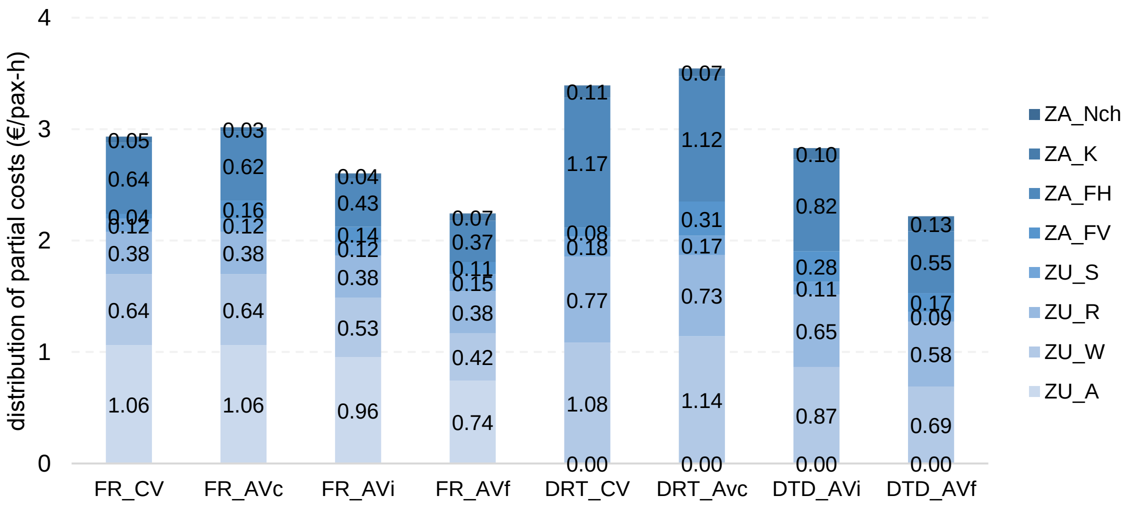
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	760.53
D_L	*(km)*	longitudinal dimension	2.39
D_W	*(km)*	transversal dimension	0.93
	(km^2)	area	2.22
γ_r	-	route factor	1.97
	(SEK/year)	household medium income	355598.29
VoT	*(€/h)*	value of time	6.85
	(pax/km^2-day)	daily demand density	1416.01
	(pax/km^2-h)	peak hour demand density	174.42
δ	*(pax/km^2-h)*	hourly demand density	94.40
	(pax/h)	hourly trips	210.01



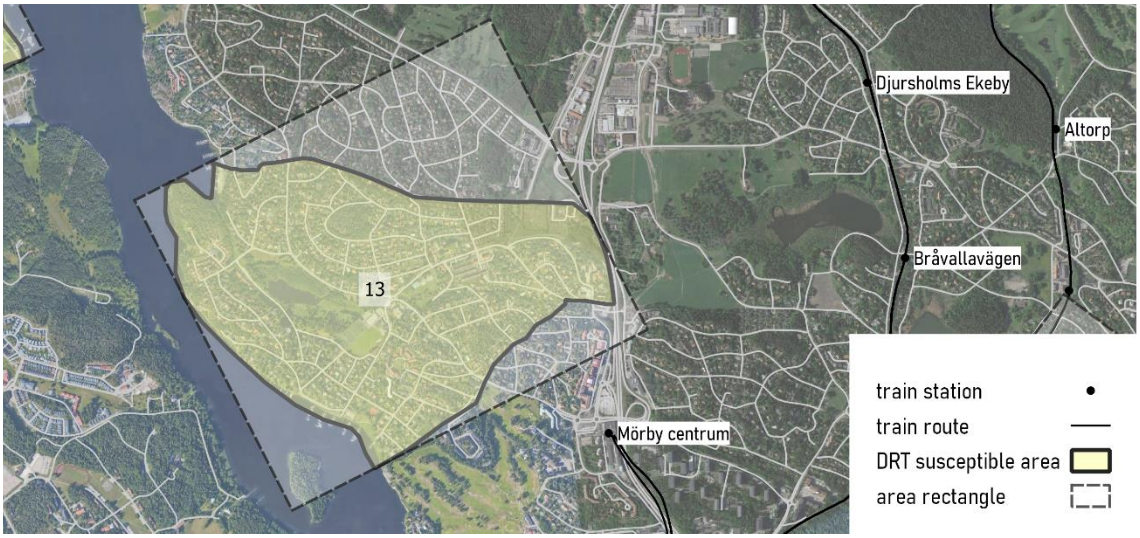
ZONE 12. Helenelund



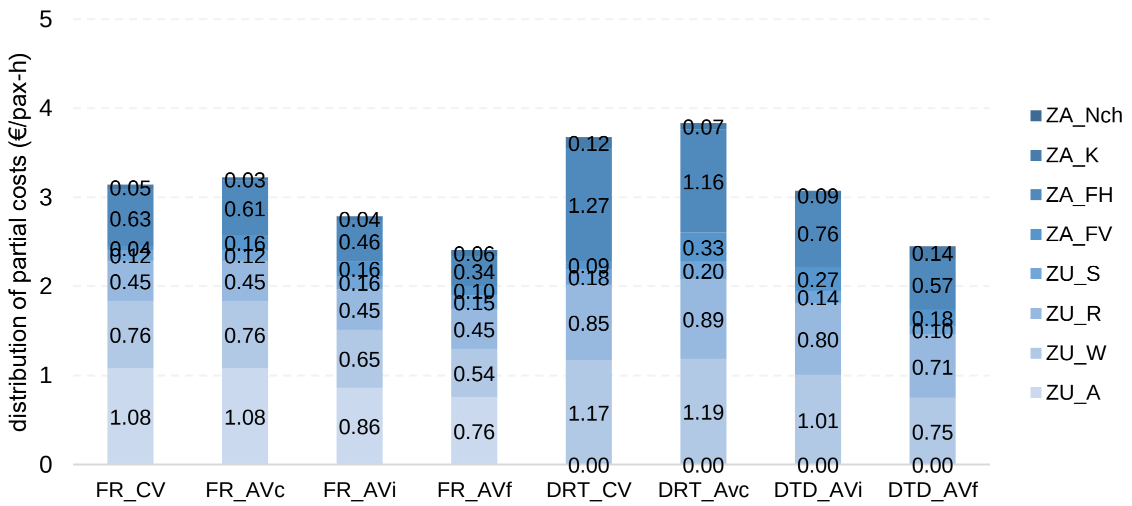
var	unit	input parameter	value
D_R	*(km)*	road length area to station	203.52
D_L	*(km)*	longitudinal dimension	1.42
D_W	*(km)*	transversal dimension	1.77
	(km^2)	area	2.52
γ_r	-	route factor	1.40
	(SEK/year)	household medium income	440744.65
VoT	*(€/h)*	value of time	8.49
	(pax/km^2-day)	daily demand density	1597.92
	(pax/km^2-h)	peak hour demand density	202.25
δ	*(pax/km^2-h)*	hourly demand density	106.53
	(pax/h)	hourly trips	268.56



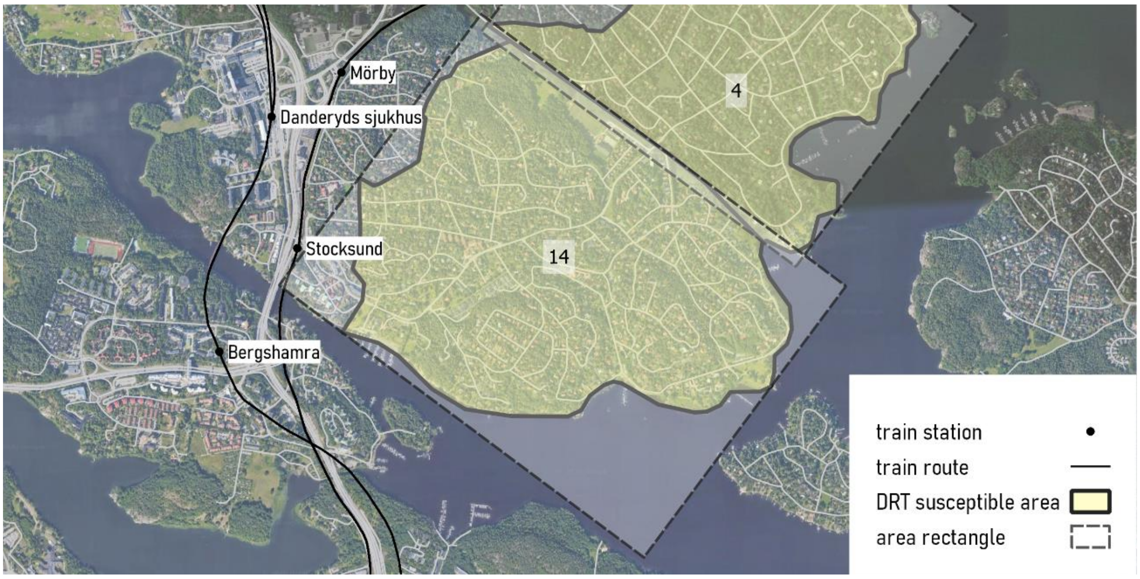
ZONE 13. Nora - Klingsta



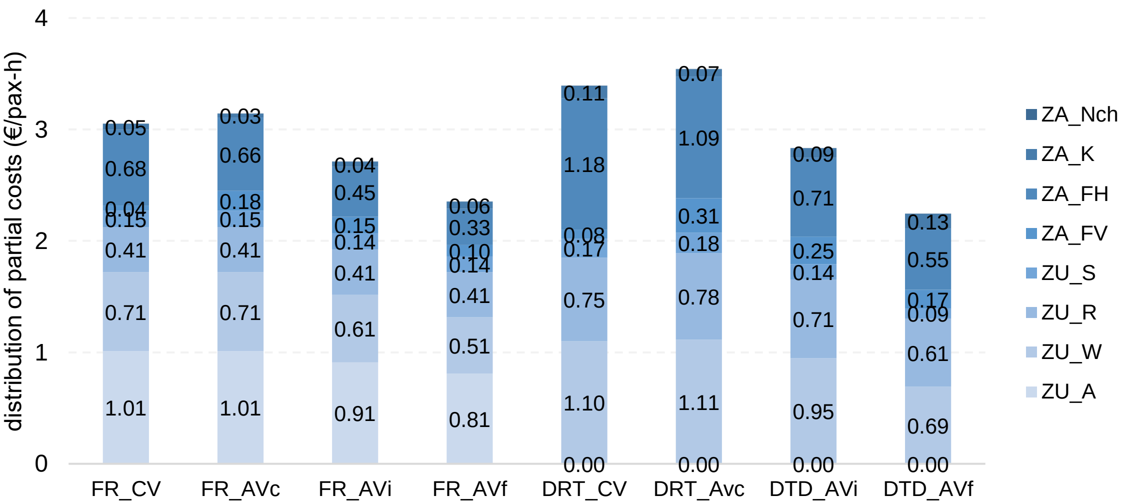
var	unit	input parameter	value
D_R	*(km)*	road length area to station	588.68
D_L	*(km)*	longitudinal dimension	1.42
D_W	*(km)*	transversal dimension	1.26
	(km²)	area	1.78
γ_r	-	route factor	1.46
	(SEK/year)	household medium income	448139.57
VoT	*(€/h)*	value of time	8.64
	(pax/km²-day)	daily demand density	1535.39
	(pax/km²-h)	peak hour demand density	193.61
δ	*(pax/km²-h)*	hourly demand density	102.36
	(pax/h)	hourly trips	182.60



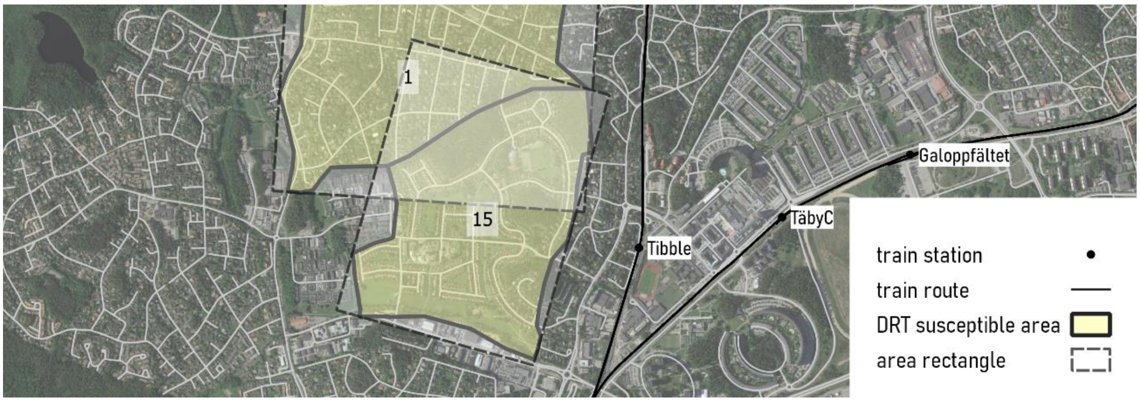
ZONE 14. Stocksund



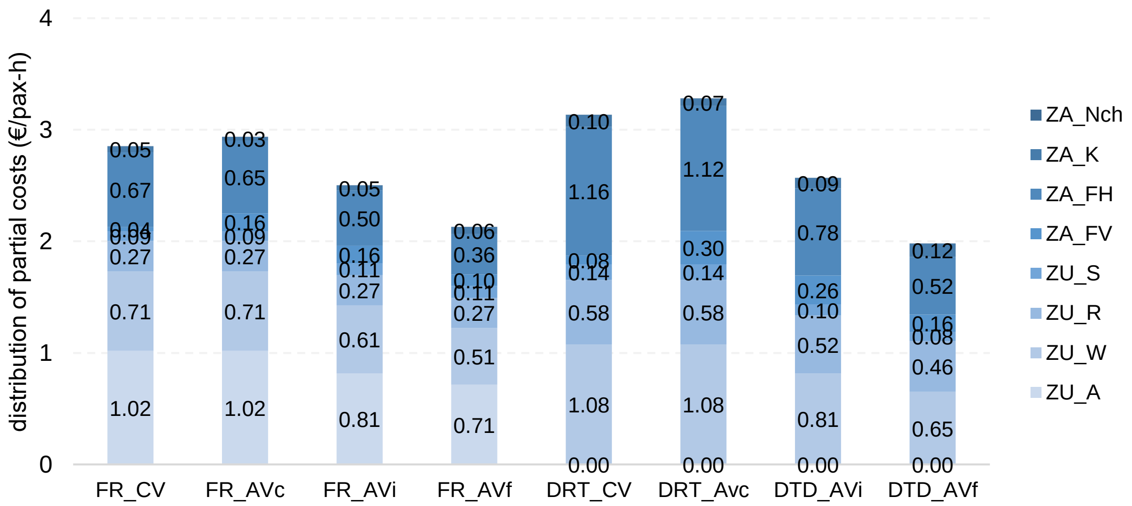
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	273.06
D_L	*(km)*	longitudinal dimension	1.94
D_W	*(km)*	transversal dimension	1.23
	(km²)	area	2.39
γ_r	-	route factor	1.22
	(SEK/year)	household medium income	419824.98
VoT	*(€/h)*	value of time	8.09
	(pax/km²-day)	daily demand density	1150.96
	(pax/km²-h)	peak hour demand density	143.89
δ	*(pax/km²-h)*	hourly demand density	76.73
	(pax/h)	hourly trips	183.42



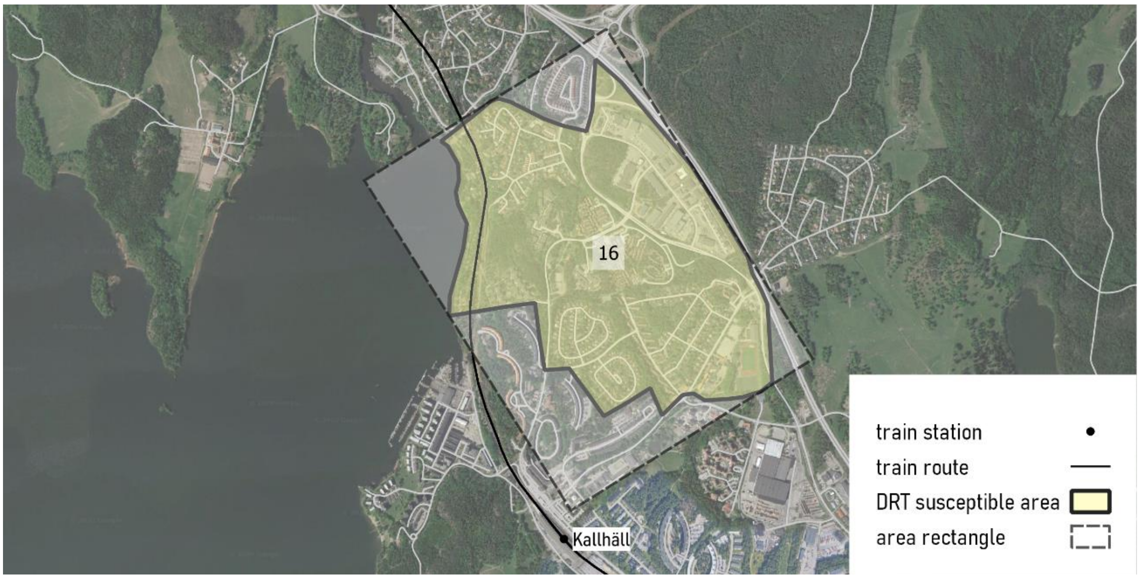
ZONE 15. Ellagård



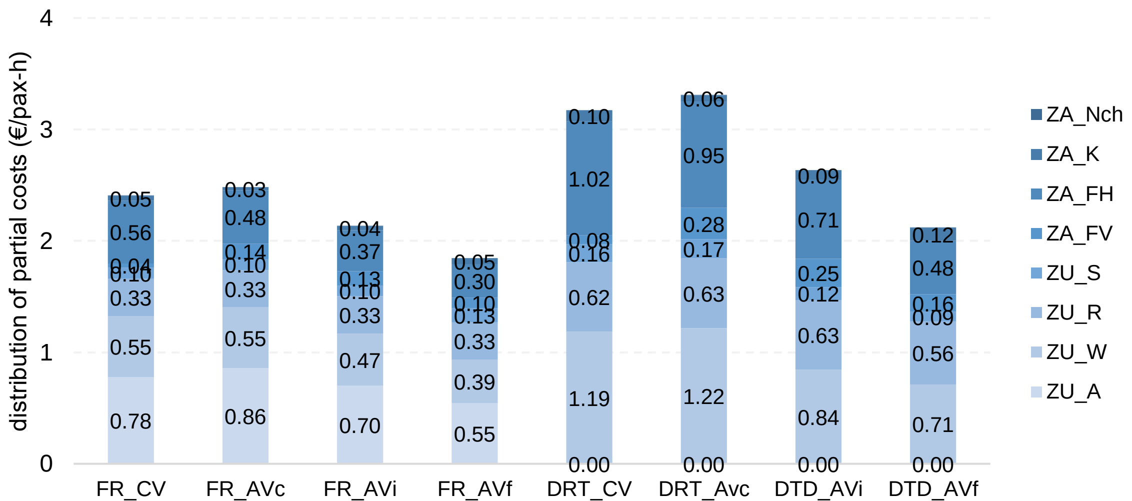
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	328.96
D_L	*(km)*	longitudinal dimension	0.87
D_W	*(km)*	transversal dimension	1.00
	(km²)	area	0.87
γ_r	-	route factor	1.3947
	(SEK/year)	household medium income	422831.05
VoT	*(€/h)*	value of time	8.15
	(pax/km²-day)	daily demand density	1428.27
	(pax/km²-h)	peak hour demand density	175.23
δ	*(pax/km²-h)*	hourly demand density	95.22
	(pax/h)	hourly trips	82.73



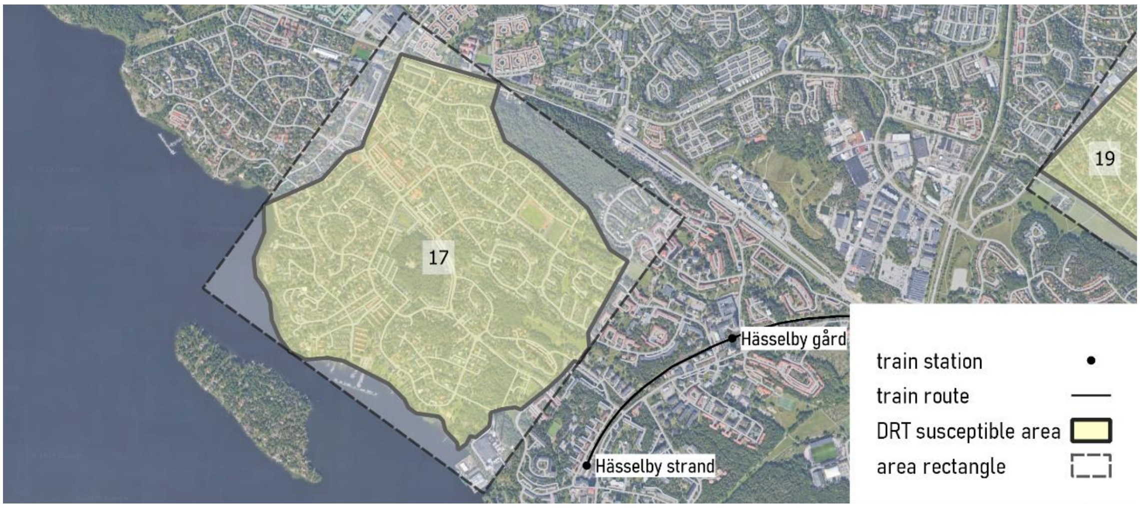
ZONE 16. Kallhäll



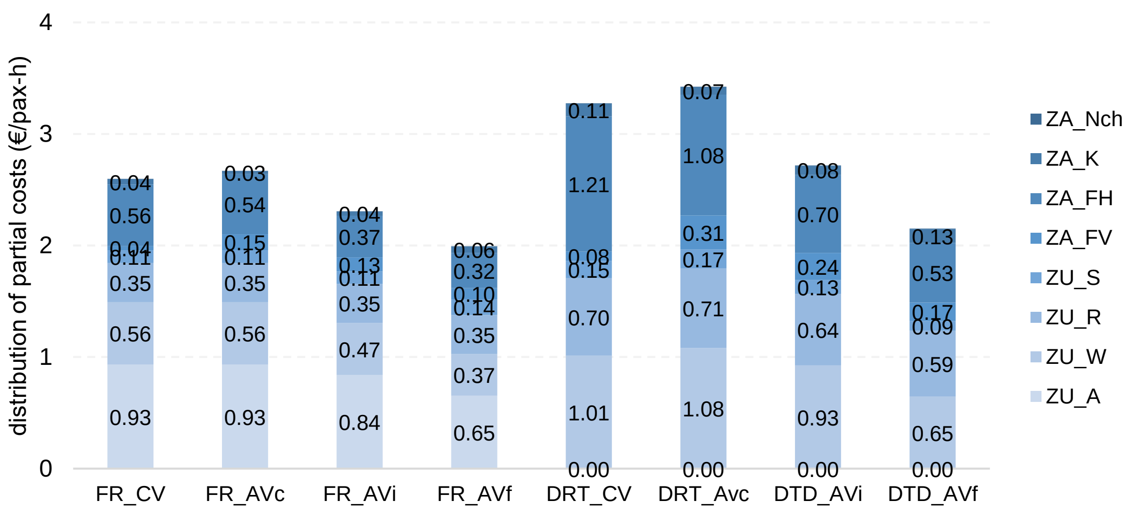
var	unit	input parameter	value
D_R	*(km)*	road length area to station	619.14
D_L	*(km)*	longitudinal dimension	1.62
D_W	*(km)*	transversal dimension	0.95
	(km²)	area	1.54
γ_r	-	route factor	1.6572
	(SEK/year)	household medium income	323412.85
VoT	*(€/h)*	value of time	6.23
	(pax/km²-day)	daily demand density	1630.84
	(pax/km²-h)	peak hour demand density	202.57
δ	*(pax/km²-h)*	hourly demand density	108.72
	(pax/h)	hourly trips	167.39



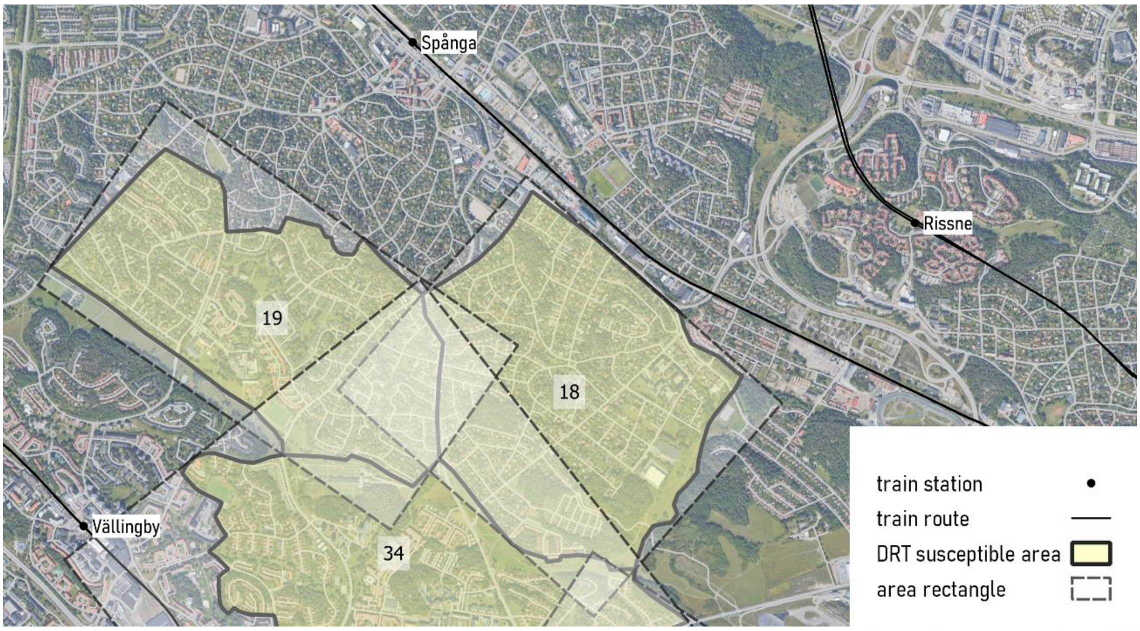
ZONE 17. Hässelby



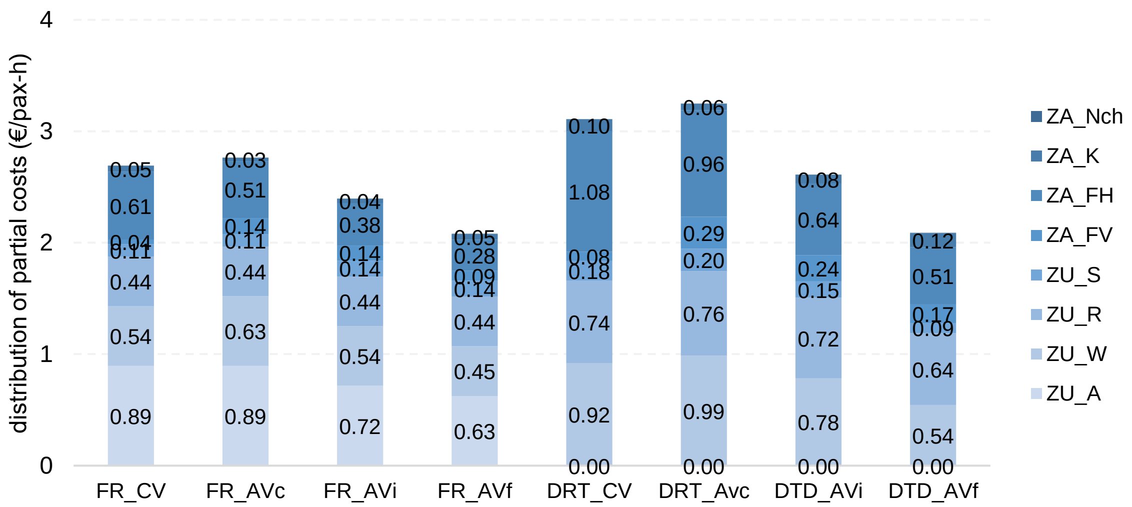
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	394.18
D_L	*(km)*	longitudinal dimension	1.48
D_W	*(km)*	transversal dimension	1.23
	(km^2)	area	1.81
γ_r	-	route factor	1.58
	(SEK/year)	household medium income	387274.69
VoT	*(€/h)*	value of time	7.46
	(pax/km^2-day)	daily demand density	1853.64
	(pax/km^2-h)	peak hour demand density	224.94
δ	*(pax/km^2-h)*	hourly demand density	123.58
	(pax/h)	hourly trips	224.09



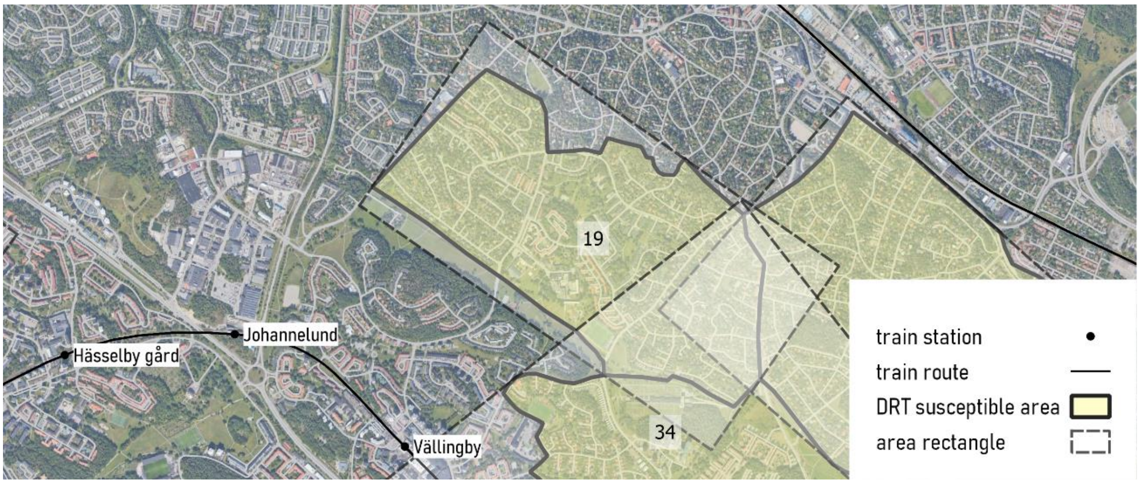
ZONE 18. Sundby - Flysta



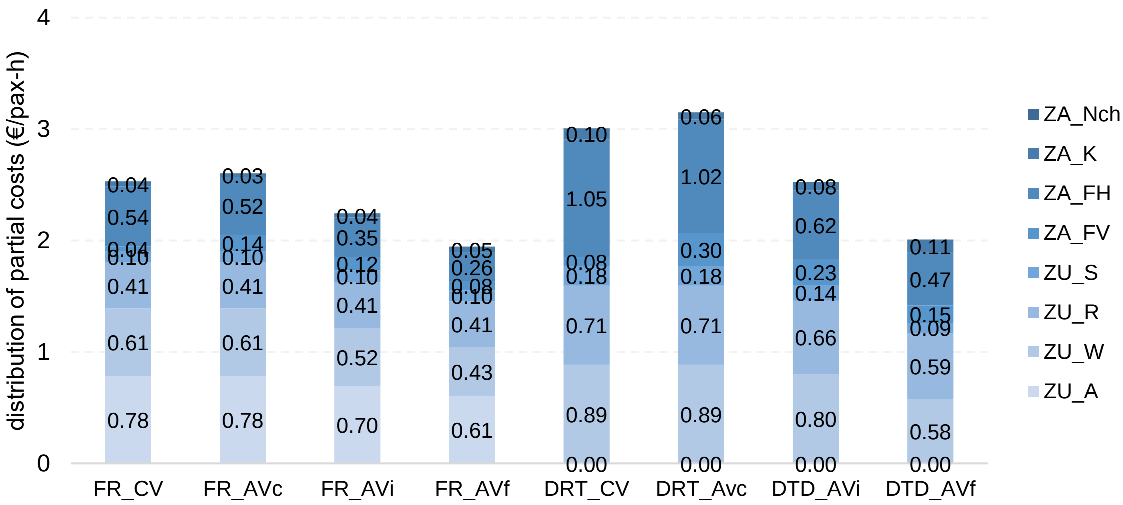
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	882.65
D_L	*(km)*	longitudinal dimension	1.48
D_W	*(km)*	transversal dimension	1.08
	(km²)	area	1.59
γ_r	-	route factor	1.1984
	(SEK/year)	household medium income	371326.61
VoT	*(€/h)*	value of time	7.16
	(pax/km²-day)	daily demand density	1952.22
	(pax/km²-h)	peak hour demand density	236.66
δ	*(pax/km²-h)*	hourly demand density	130.15
	(pax/h)	hourly trips	207.38



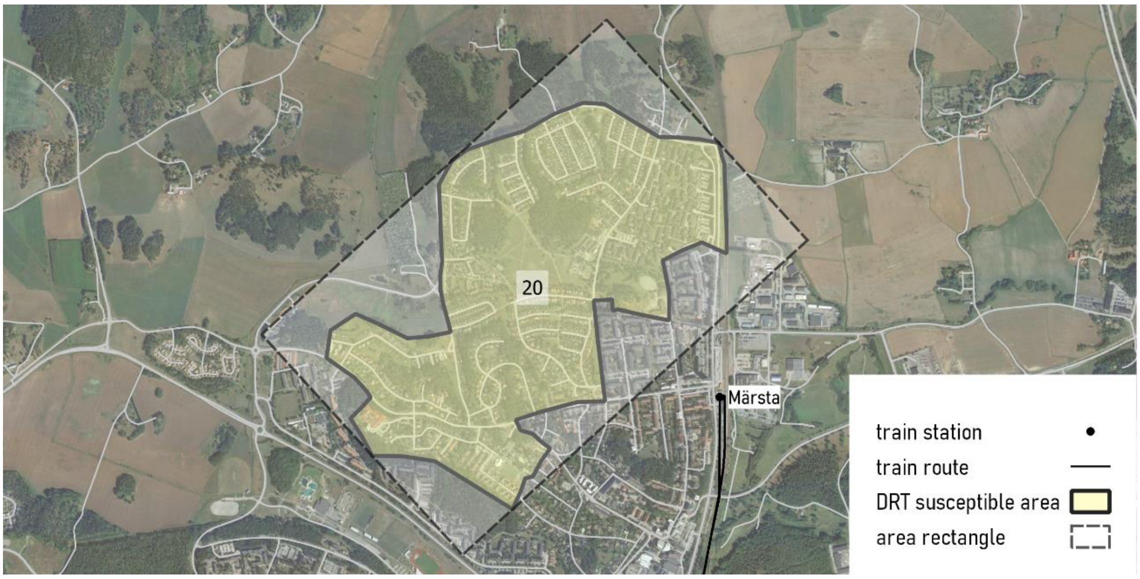
ZONE 19. Nälsta



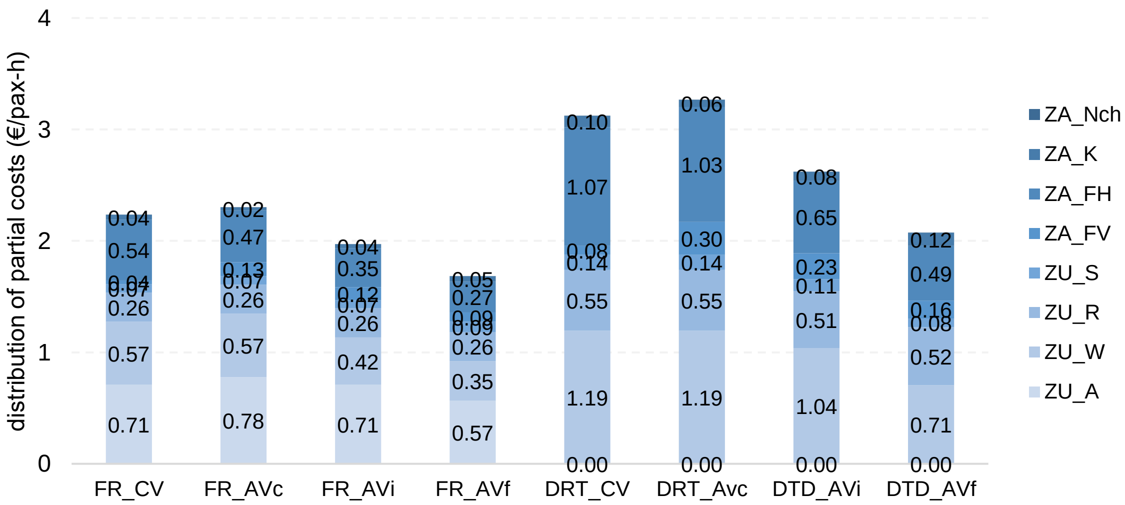
var	unit	input parameter	value
D_R	*(km)*	road length area to station	936.87
D_L	*(km)*	longitudinal dimension	0.94
D_W	*(km)*	transversal dimension	1.51
	(km^2)	area	1.42
γ_r	-	route factor	1.36
	(SEK/year)	household medium income	360806.55
VoT	*(€/h)*	value of time	6.95
	(pax/km^2-day)	daily demand density	2732.83
	(pax/km^2-h)	peak hour demand density	329.33
δ	*(pax/km^2-h)*	hourly demand density	182.19
	(pax/h)	hourly trips	259.33



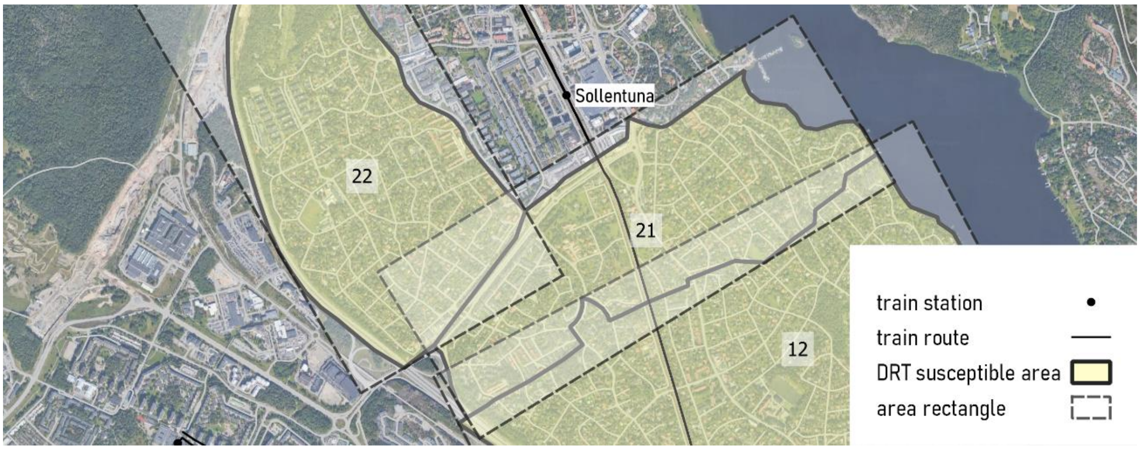
ZONE 20. Märsta



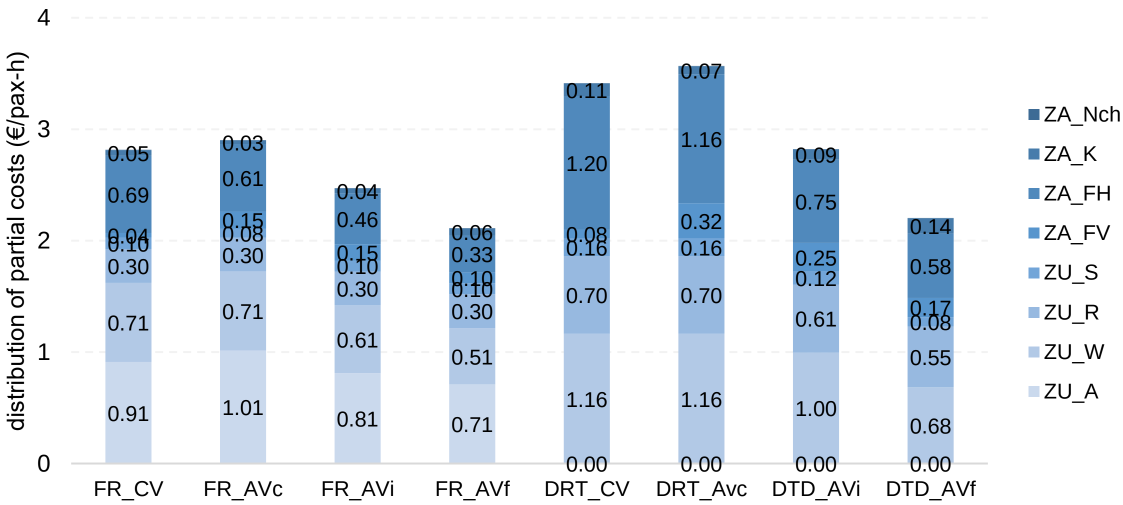
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	443.44
D_L	*(km)*	longitudinal dimension	1.21
D_W	*(km)*	transversal dimension	1.45
	(km²)	area	1.76
γ_r	-	route factor	2.0943
	(SEK/year)	household medium income	293981.59
VoT	*(€/h)*	value of time	5.67
	(pax/km²-day)	daily demand density	1619.77
	(pax/km²-h)	peak hour demand density	196.24
δ	*(pax/km²-h)*	hourly demand density	107.98
	(pax/h)	hourly trips	189.75



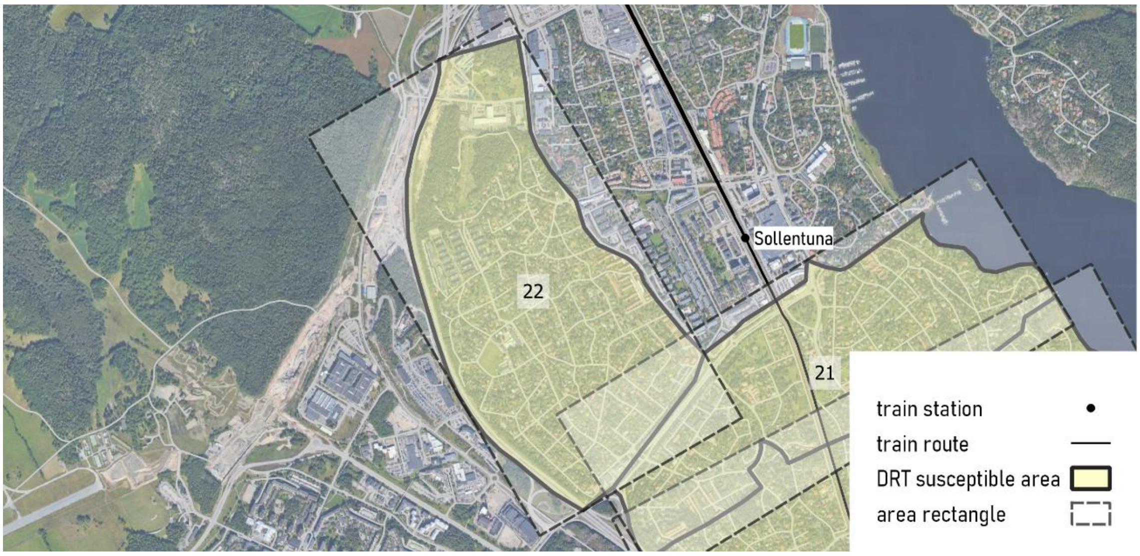
ZONE 21. Fågelsången - Skansen



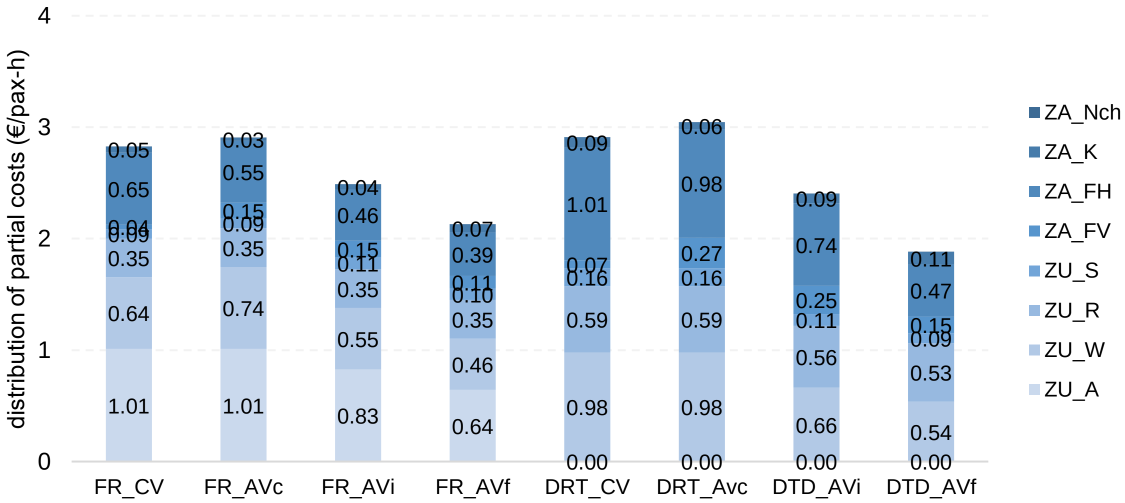
var	unit	input parameter	value
D_R	(km)	road length area to station	313.13
D_L	(km)	longitudinal dimension	0.81
D_W	(km)	transversal dimension	1.61
	(km^2)	area	1.30
γ_r	-	route factor	1.7573
	(SEK/year)	household medium income	420682.54
VoT	(€/h)	value of time	8.11
	(pax/km^2-day)	daily demand density	1759.58
	(pax/km^2-h)	peak hour demand density	222.22
δ	(pax/km^2-h)	hourly demand density	117.31
	(pax/h)	hourly trips	152.24



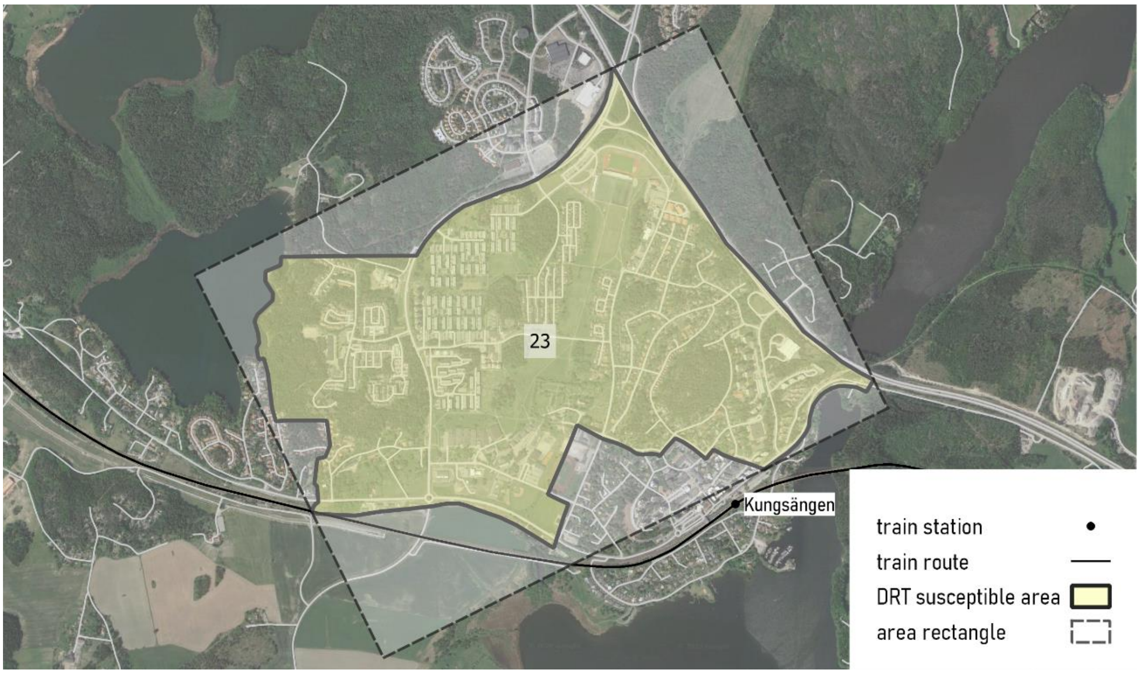
ZONE 22. Töjnan



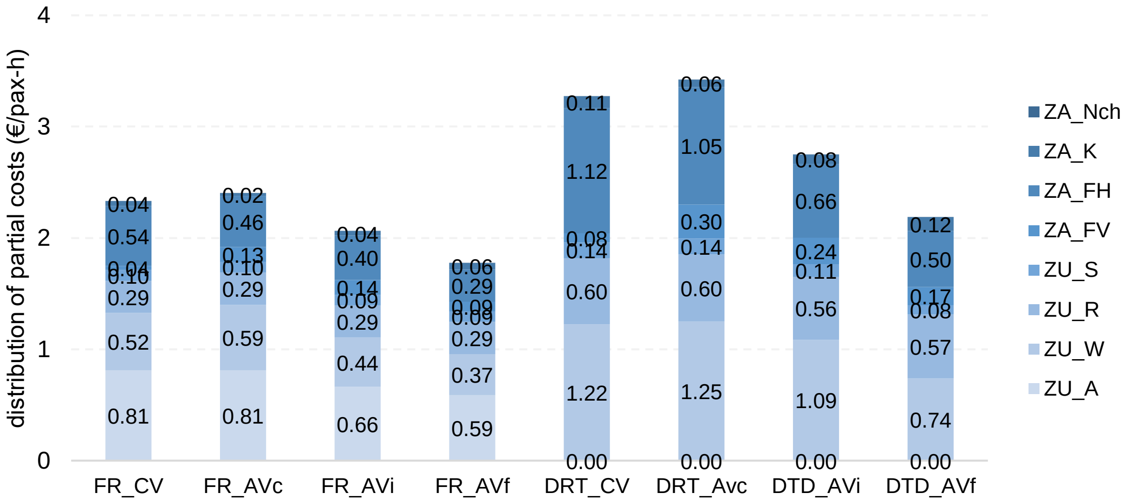
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	511.21
D_L	*(km)*	longitudinal dimension	0.99
D_W	*(km)*	transversal dimension	1.63
	(km^2)	area	1.62
γ_r	-	route factor	1.0859
	(SEK/year)	household medium income	381507.12
VoT	*(€/h)*	value of time	7.35
	(pax/km^2-day)	daily demand density	1488.86
	(pax/km^2-h)	peak hour demand density	187.99
δ	*(pax/km^2-h)*	hourly demand density	99.26
	(pax/h)	hourly trips	160.67



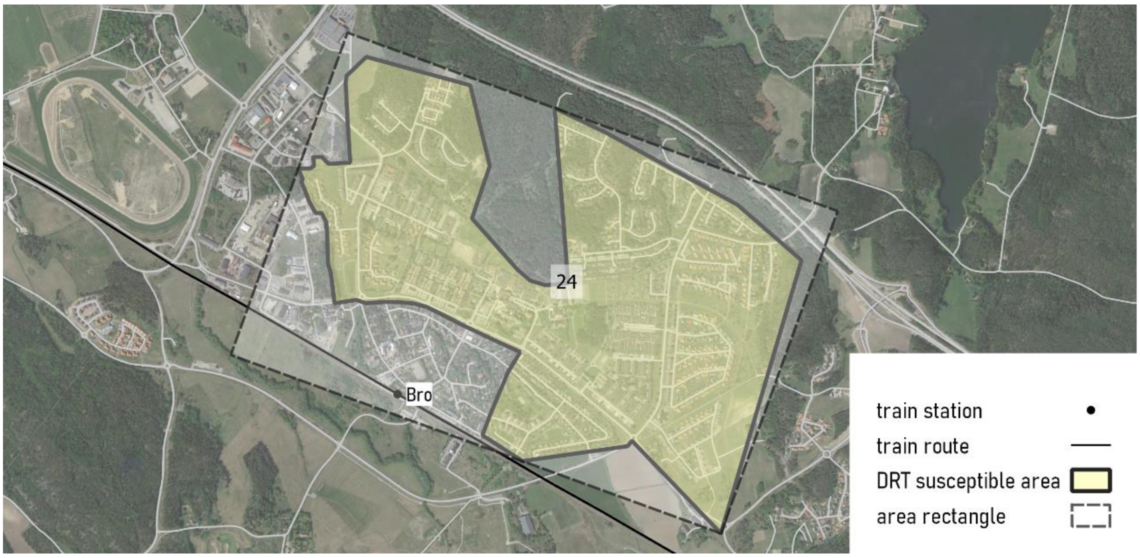
ZONE 23. Kungsängen



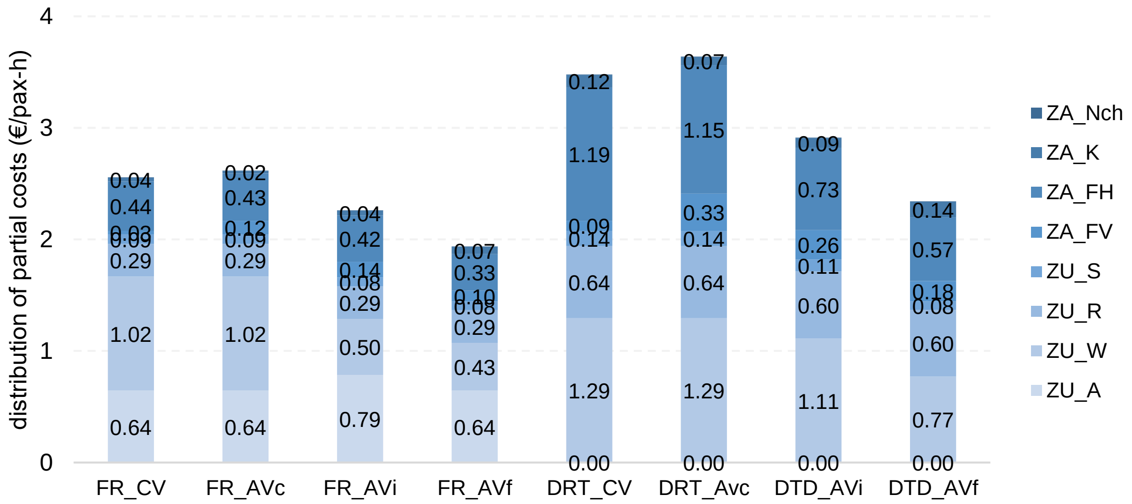
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	197.41
D_L	*(km)*	longitudinal dimension	1.74
D_W	*(km)*	transversal dimension	1.78
	(km²)	area	3.09
γ_r	-	route factor	2.0154
	(SEK/year)	household medium income	305791.31
VoT	*(€/h)*	value of time	5.89
	(pax/km²-day)	daily demand density	1390.56
	(pax/km²-h)	peak hour demand density	172.21
δ	*(pax/km²-h)*	hourly demand density	92.70
	(pax/h)	hourly trips	286.40



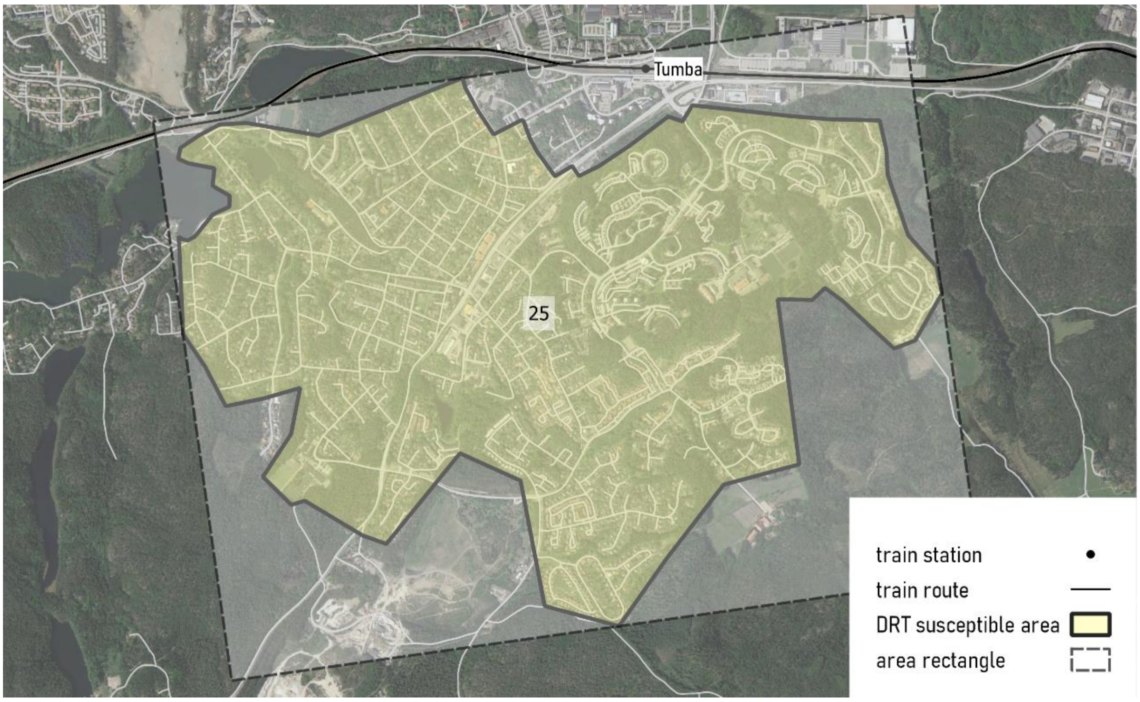
ZONE 24. Bro



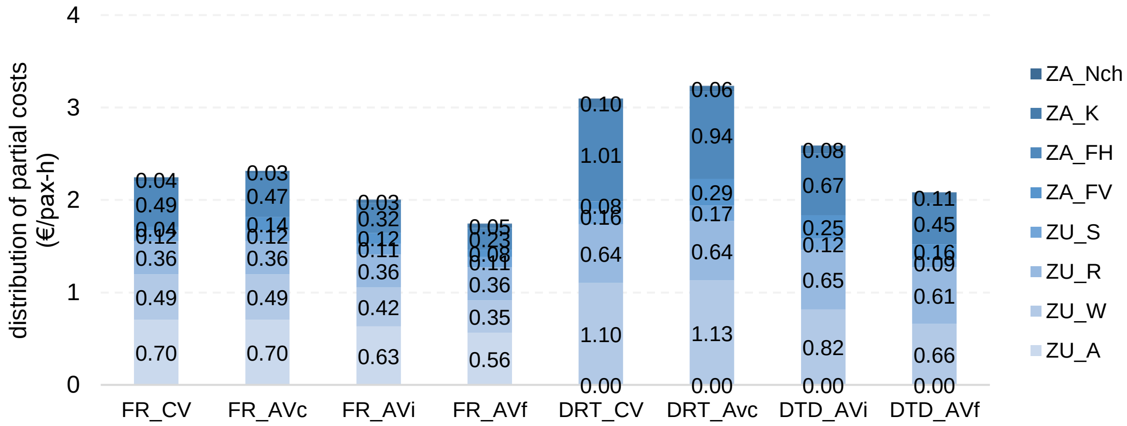
var	unit	input parameter	value
D_R	(km)	road length area to station	422.79
D_L	(km)	longitudinal dimension	1.41
D_W	(km)	transversal dimension	1.71
	(km^2)	area	2.42
γ_r	-	route factor	2.0907
	(SEK/year)	household medium income	296806.94
VoT	(€/h)	value of time	5.72
	(pax/km^2-day)	daily demand density	965.83
	(pax/km^2-h)	peak hour demand density	123.04
δ	(pax/km^2-h)	hourly demand density	64.39
	(pax/h)	hourly trips	155.72



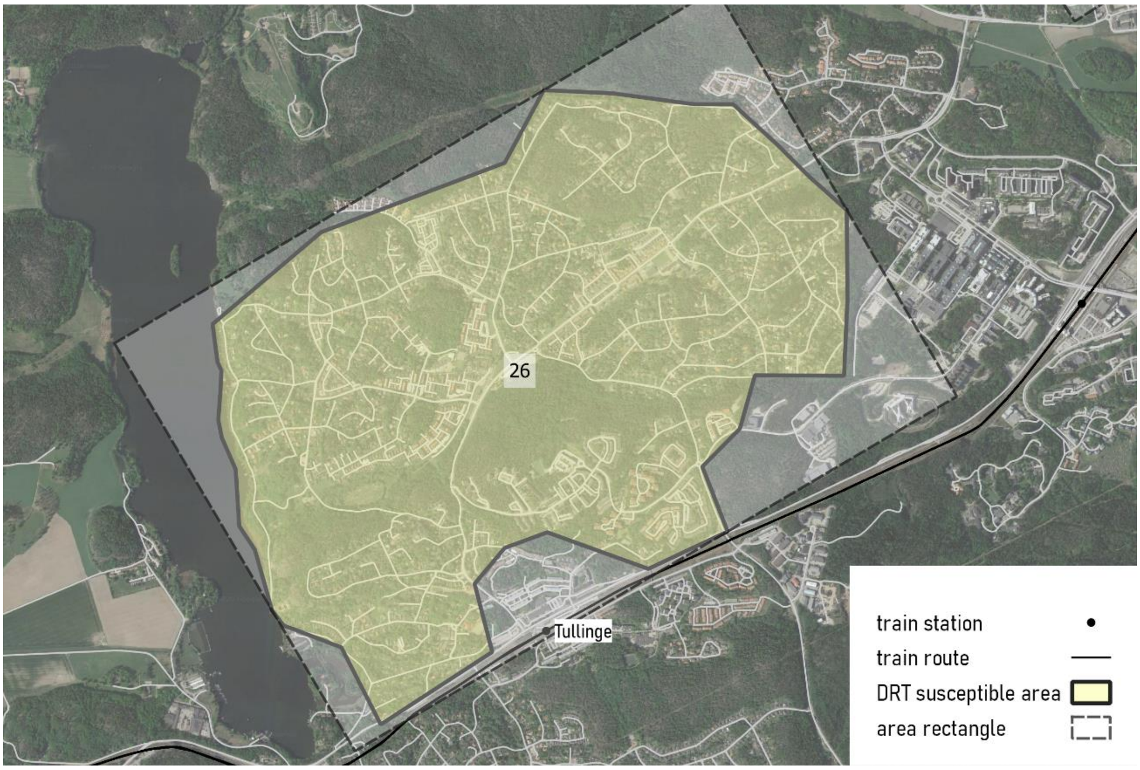
ZONE 25. Tumba



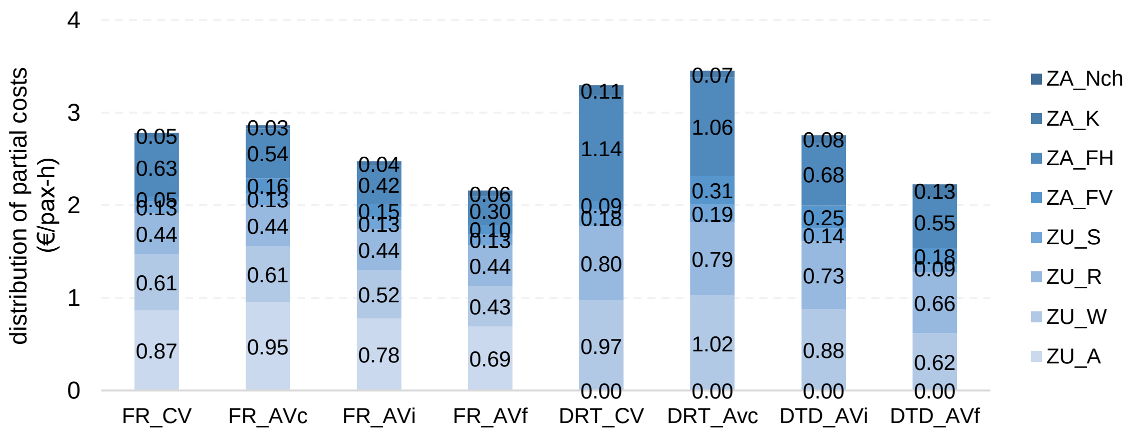
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	244.77
D_L	*(km)*	longitudinal dimension	2.29
D_W	*(km)*	transversal dimension	2.35
	(km²)	area	5.37
γ_r	-	route factor	1.6601
	(SEK/year)	household medium income	291816.89
VoT	*(€/h)*	value of time	5.62
	(pax/km²-day)	daily demand density	1763.46
	(pax/km²-h)	peak hour demand density	222.45
δ	*(pax/km²-h)*	hourly demand density	117.56
	(pax/h)	hourly trips	631.86



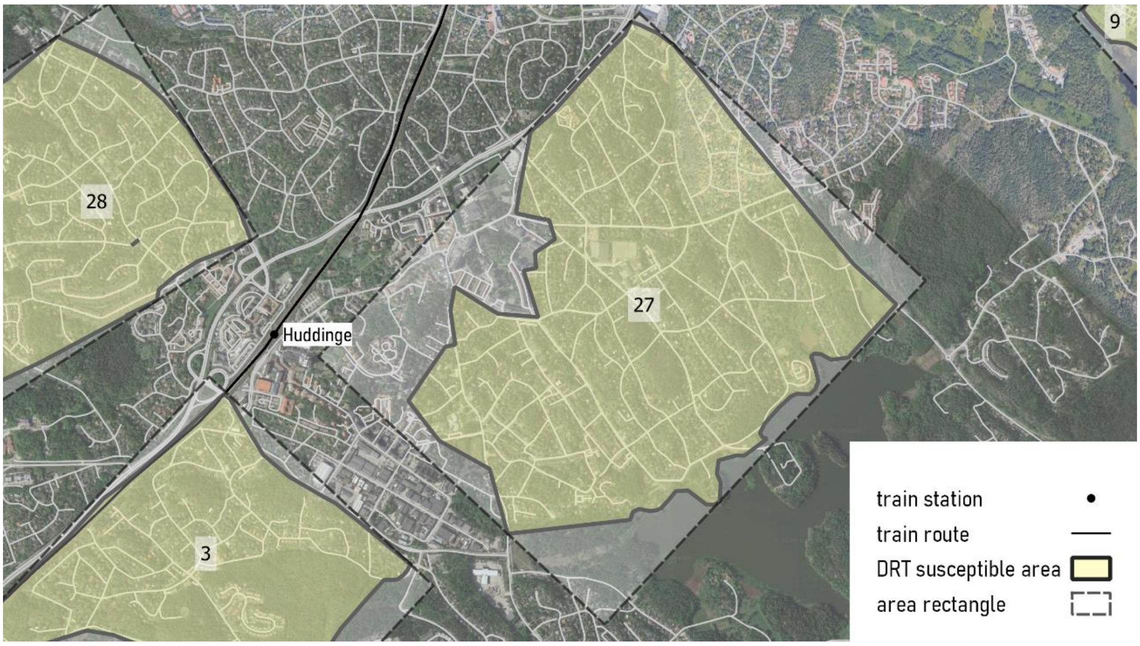
ZONE 26. Tullinge



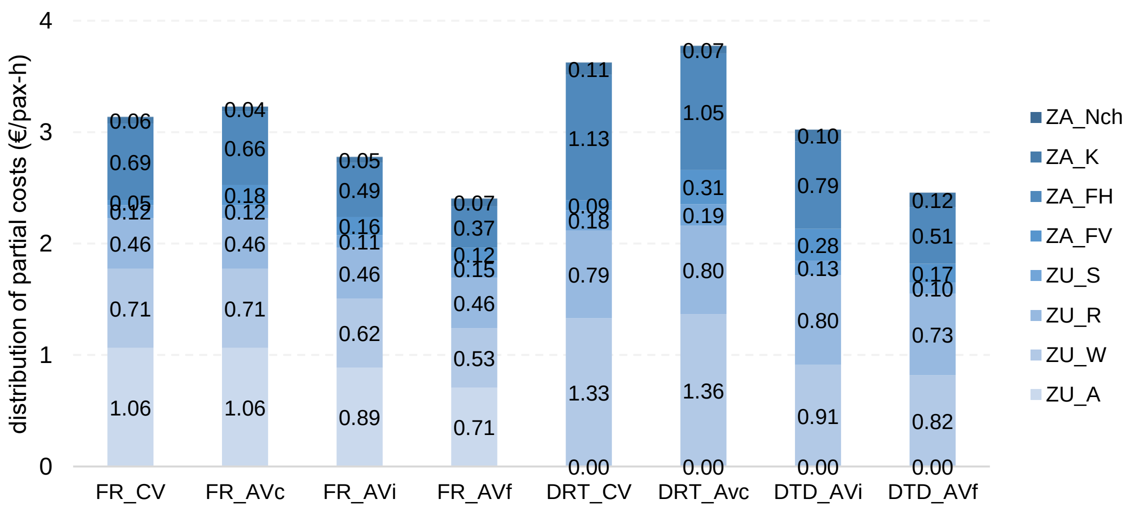
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	266.65
D_L	*(km)*	longitudinal dimension	2.03
D_W	*(km)*	transversal dimension	2.57
	(km²)	area	5.21
γ_r	-	route factor	1.2704
	(SEK/year)	household medium income	359871.38
VoT	*(€/h)*	value of time	6.94
	(pax/km²-day)	daily demand density	1370.75
	(pax/km²-h)	peak hour demand density	171.23
δ	*(pax/km²-h)*	hourly demand density	91.38
	(pax/h)	hourly trips	476.11



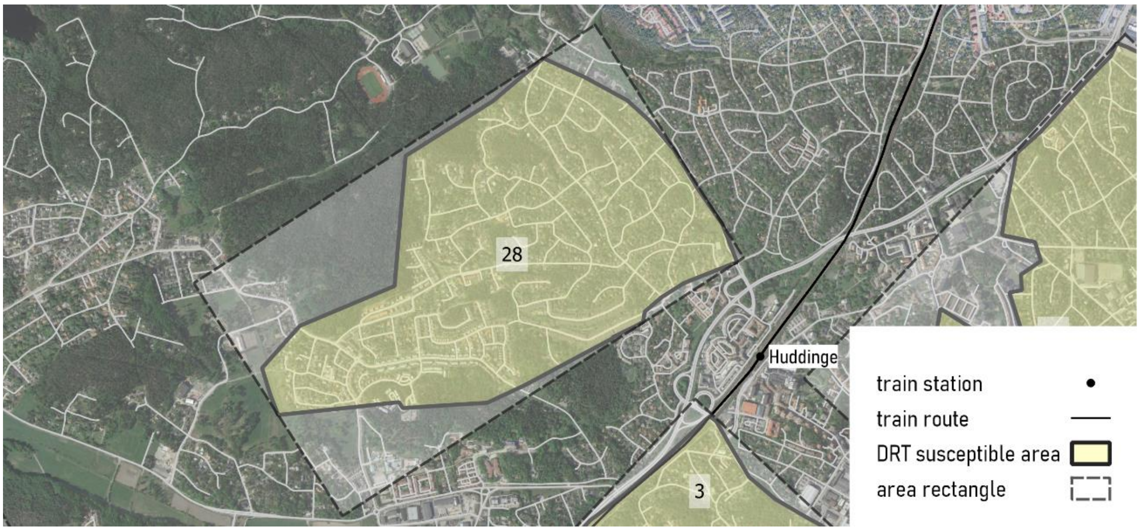
ZONE 27. Huddinge - Kynäs



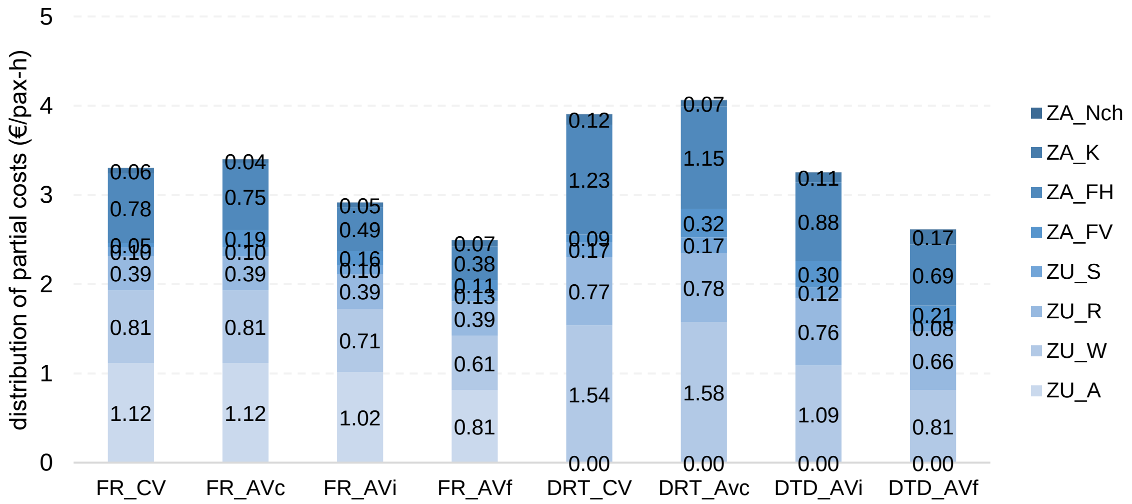
var	unit	input parameter	value
D_R	*(km)*	road length area to station	692.35
D_L	*(km)*	longitudinal dimension	1.67
D_W	*(km)*	transversal dimension	1.70
	(km^2)	area	2.85
γ_r	-	route factor	1.348
	(SEK/year)	household medium income	368084.23
VoT	*(€/h)*	value of time	7.09
	(pax/km^2-day)	daily demand density	959.34
	(pax/km^2-h)	peak hour demand density	120.93
δ	*(pax/km^2-h)*	hourly demand density	63.96
	(pax/h)	hourly trips	182.21



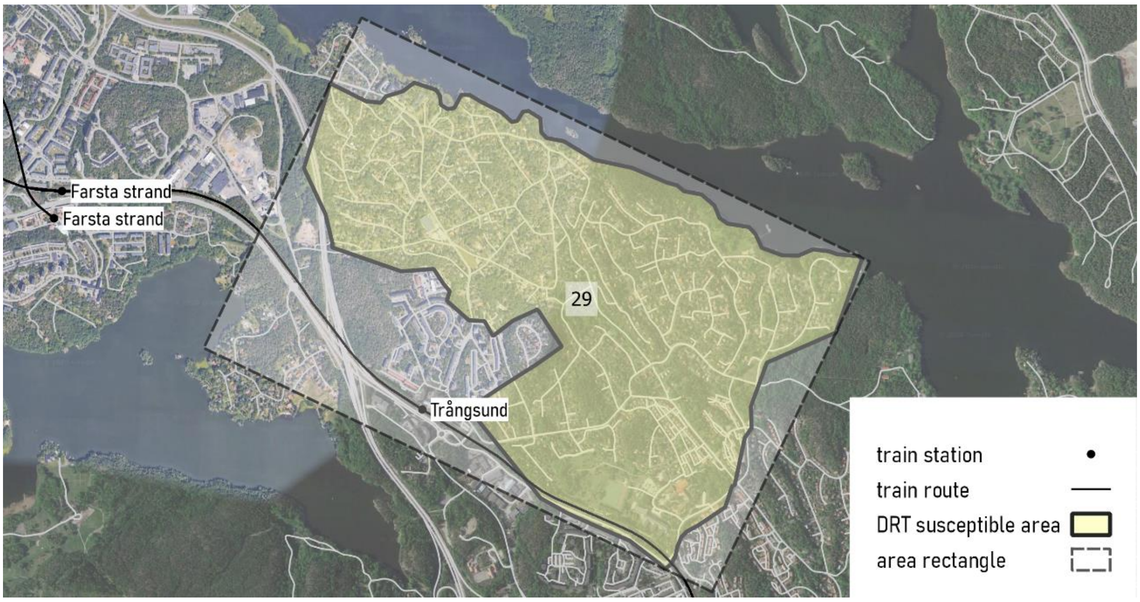
ZONE 28. Huddinge - Vistaberg



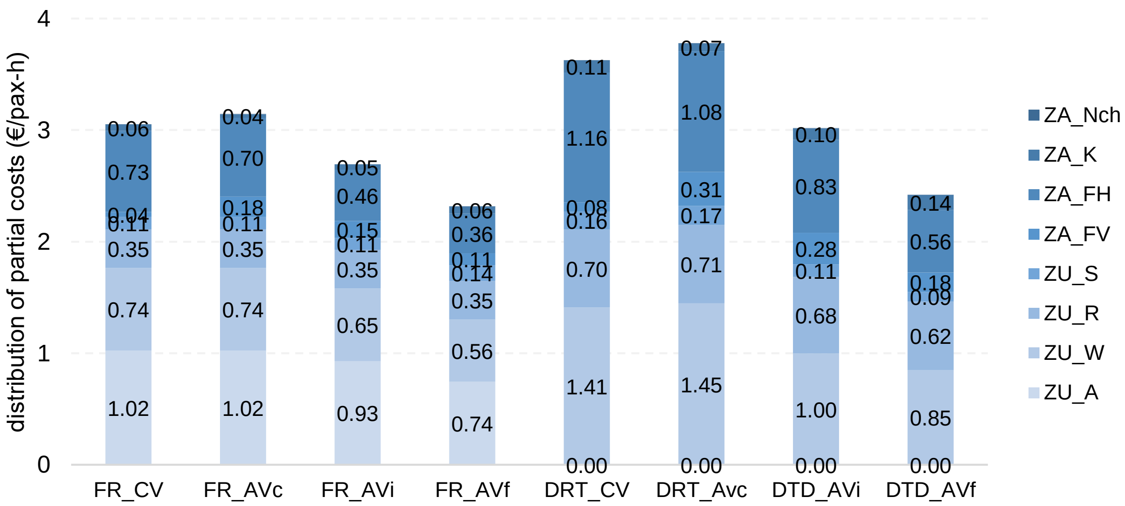
var	unit	input parameter	value
D_R	*(km)*	road length area to station	446.23
D_L	*(km)*	longitudinal dimension	1.16
D_W	*(km)*	transversal dimension	1.66
	(km²)	area	1.92
γ_r	-	route factor	1.6768
	(SEK/year)	household medium income	421333.49
VoT	*(€/h)*	value of time	8.12
	(pax/km²-day)	daily demand density	989.29
	(pax/km²-h)	peak hour demand density	124.70
δ	*(pax/km²-h)*	hourly demand density	65.95
	(pax/h)	hourly trips	126.89



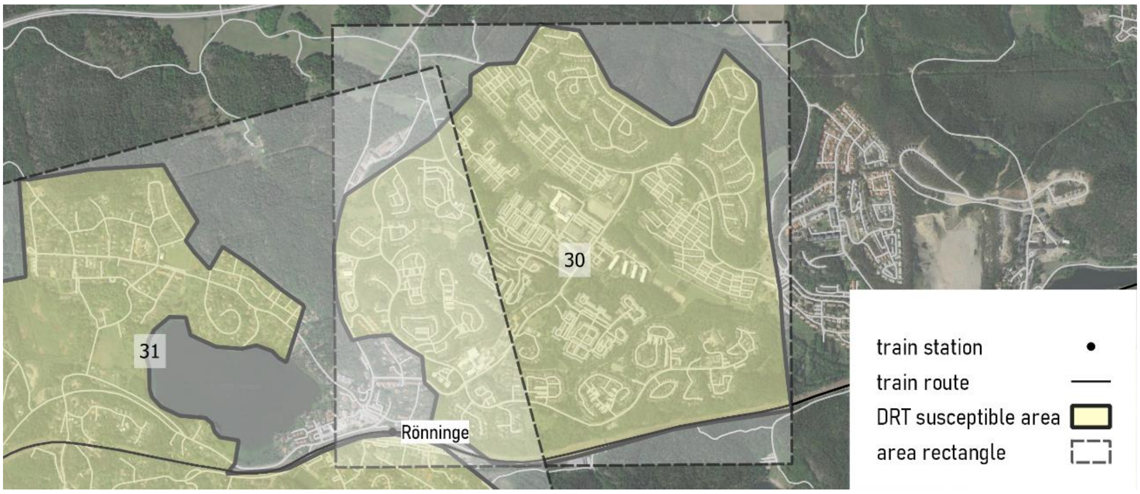
ZONE 29. Trångsund



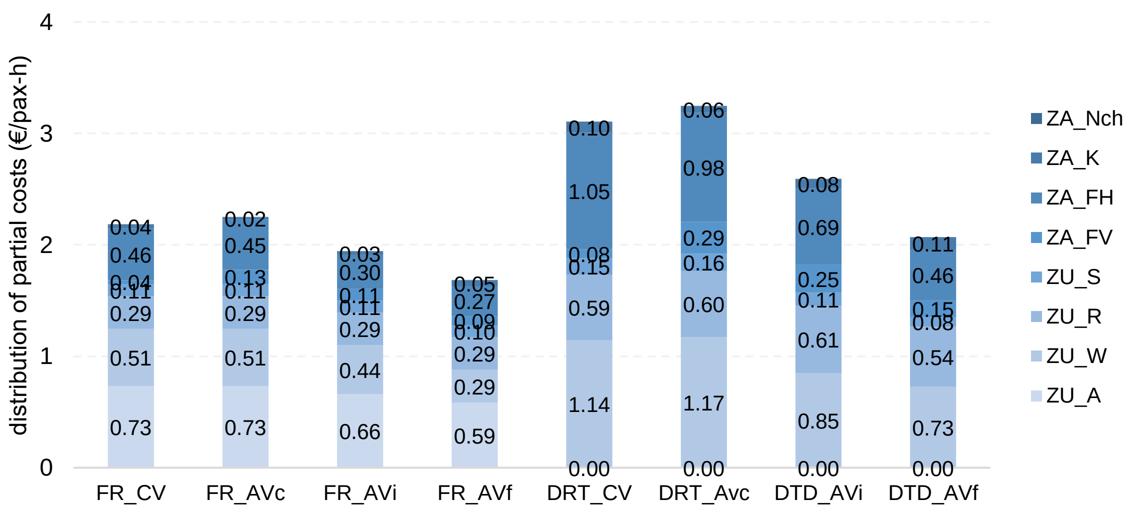
var	unit	input parameter	value
D_R	*(km)*	road length area to station	223.30
D_L	*(km)*	longitudinal dimension	1.50
D_W	*(km)*	transversal dimension	1.83
	(km²)	area	2.75
γ_r	-	route factor	1.5669
	(SEK/year)	household medium income	385428.14
VoT	*(€/h)*	value of time	7.43
	(pax/km²-day)	daily demand density	920.47
	(pax/km²-h)	peak hour demand density	118.85
δ	*(pax/km²-h)*	hourly demand density	61.36
	(pax/h)	hourly trips	168.65



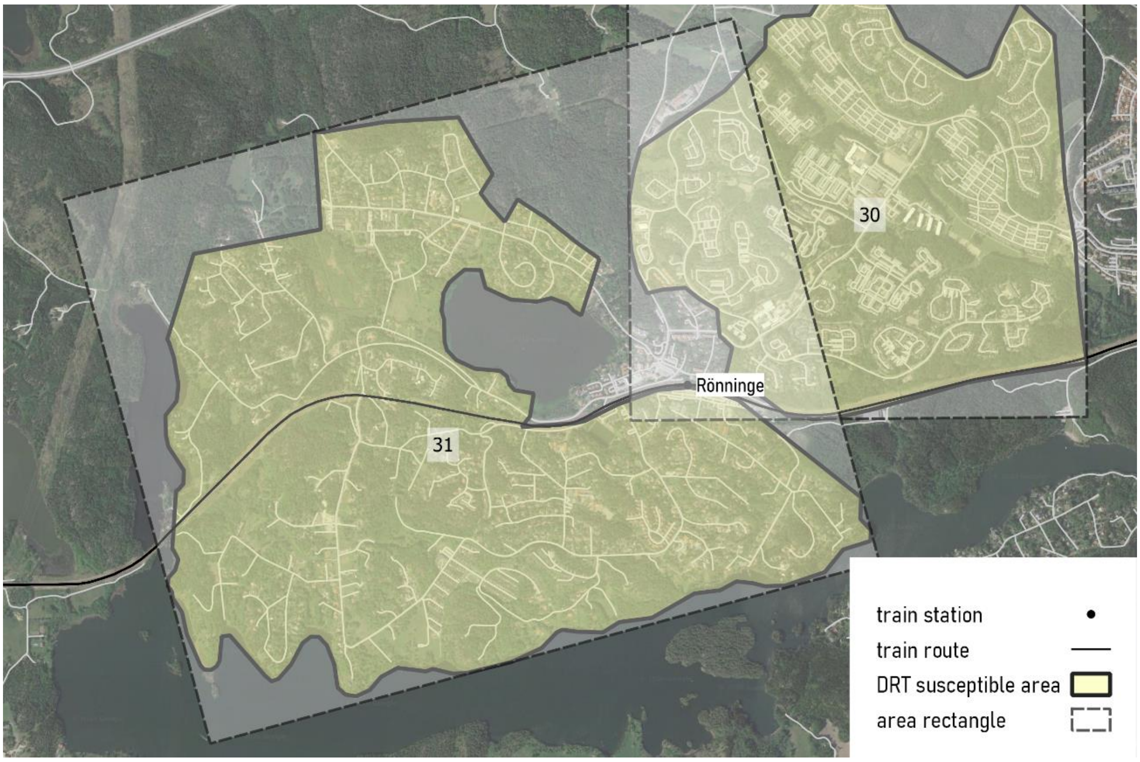
ZONE 30. Rönninge - Salems



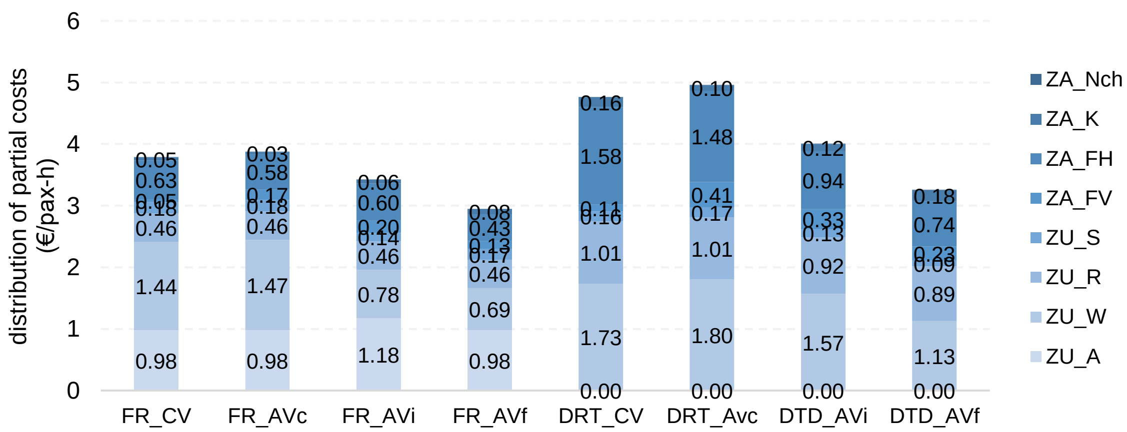
var	unit	input parameter	value
D_R	(km)	road length area to station	188.32
D_L	(km)	longitudinal dimension	1.93
D_W	(km)	transversal dimension	1.57
	(km^2)	area	3.03
γ_r	-	route factor	1.9062
	(SEK/year)	household medium income	304002.33
VoT	(€/h)	value of time	5.86
	(pax/km^2-day)	daily demand density	1762.64
	(pax/km^2-h)	peak hour demand density	223.47
δ	(pax/km^2-h)	hourly demand density	117.51
	(pax/h)	hourly trips	355.60



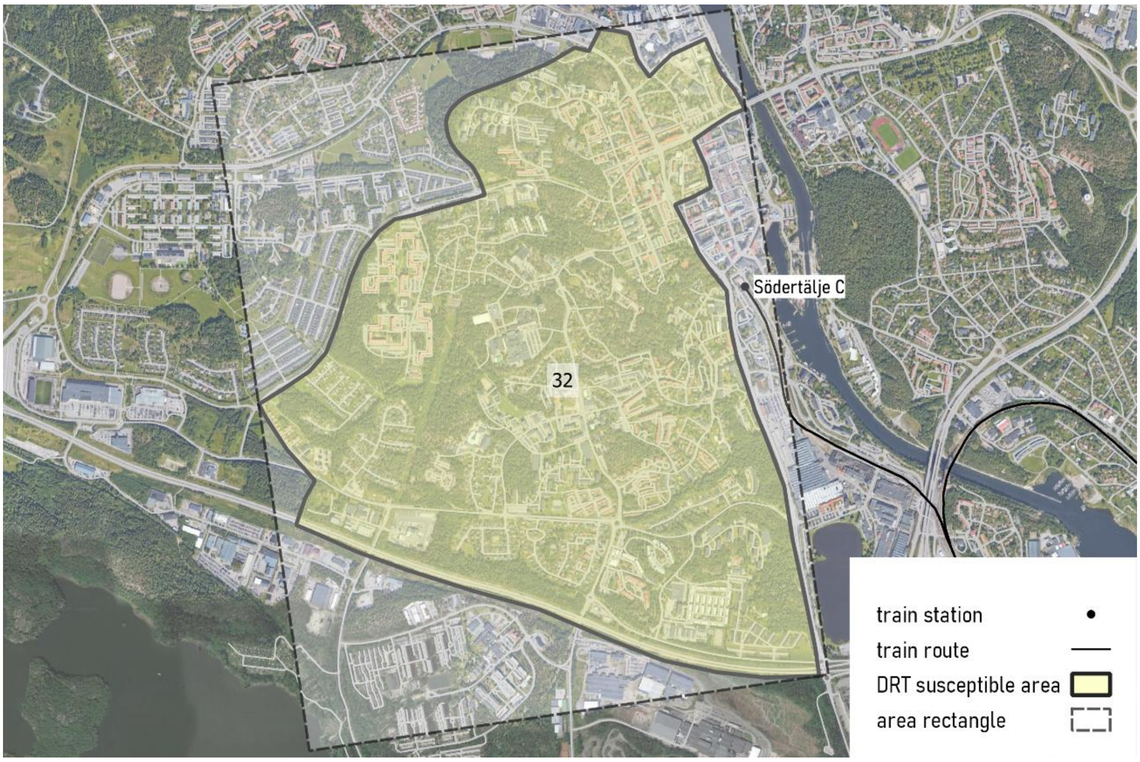
ZONE 31. Rönninge - Uttringe



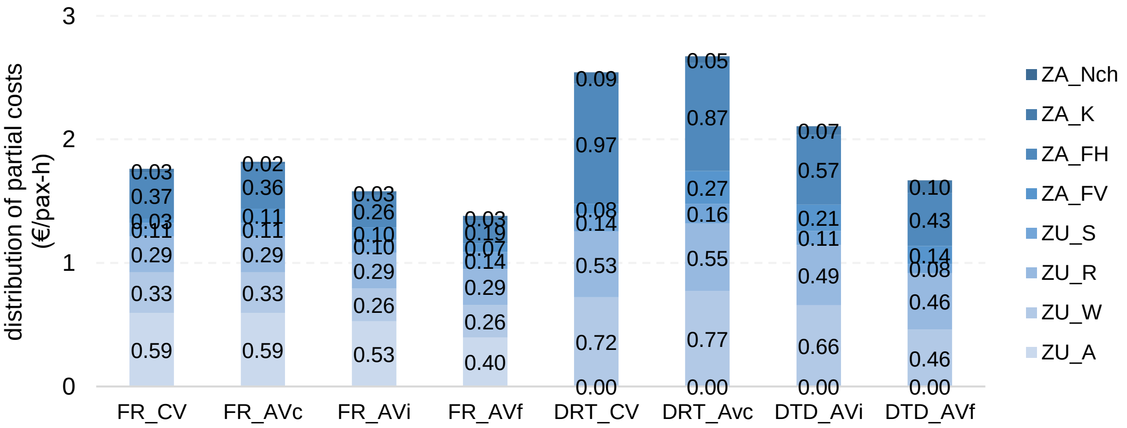
var	unit	input parameter	value
D_R	*(km)*	road length area to station	42.17
D_L	*(km)*	longitudinal dimension	2.80
D_W	*(km)*	transversal dimension	1.74
	(km^2)	area	4.87
γ_r	-	route factor	1.8315
	(SEK/year)	household medium income	406478.69
VoT	*(€/h)*	value of time	7.83
	(pax/km^2-day)	daily demand density	412.14
	(pax/km^2-h)	peak hour demand density	53.15
δ	*(pax/km^2-h)*	hourly demand density	27.48
	(pax/h)	hourly trips	133.81



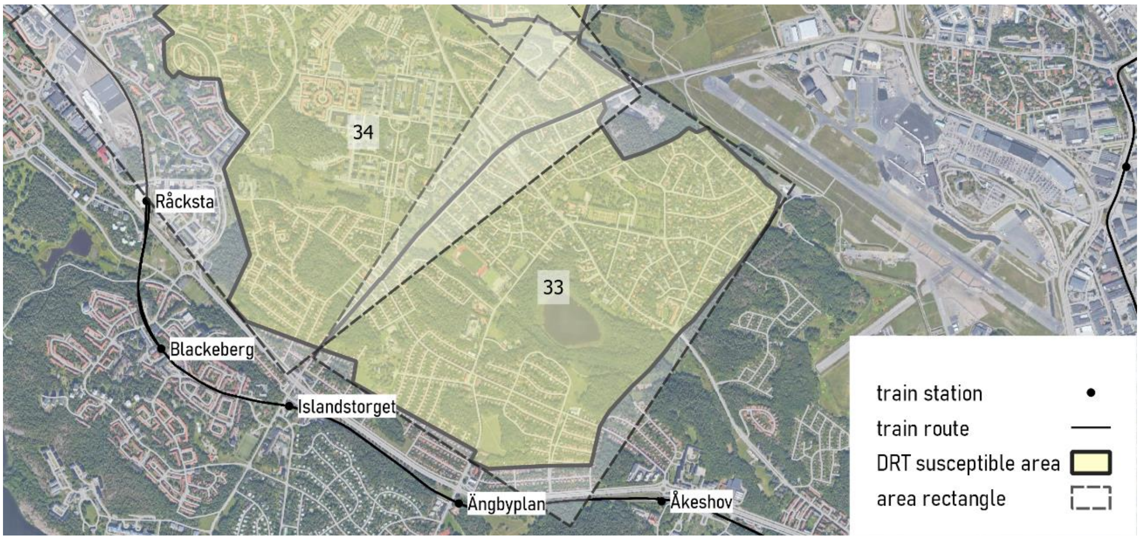
ZONE 32. Södertälje



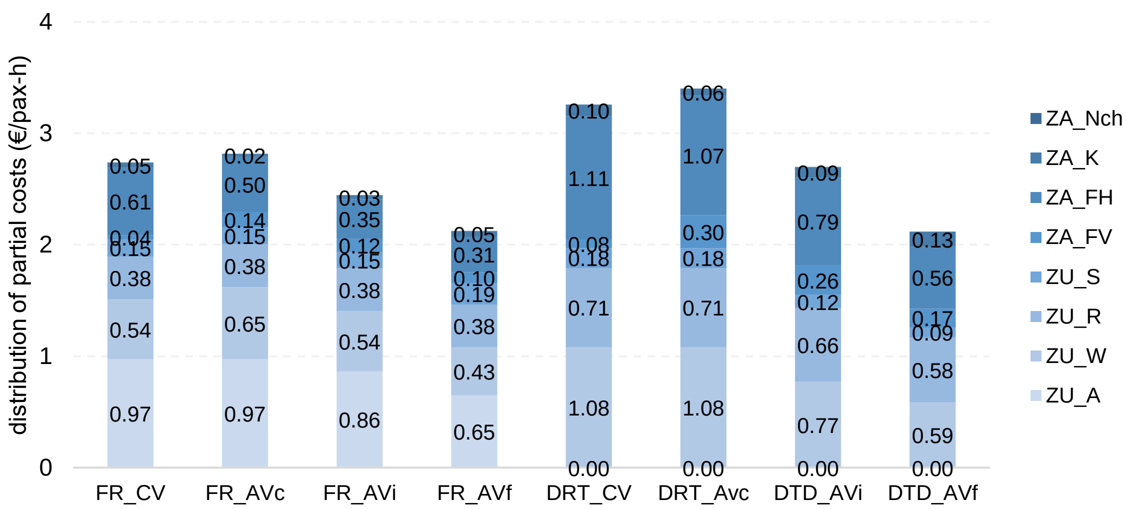
var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	94.50
D_L	*(km)*	longitudinal dimension	2.15
D_W	*(km)*	transversal dimension	2.15
	(km²)	area	4.62
γ_r	-	route factor	1.6031
	(SEK/year)	household medium income	274148.12
VoT	*(€/h)*	value of time	5.28
	(pax/km²-day)	daily demand density	3729.44
	(pax/km²-h)	peak hour demand density	456.51
δ	*(pax/km²-h)*	hourly demand density	248.63
	(pax/h)	hourly trips	1149.39



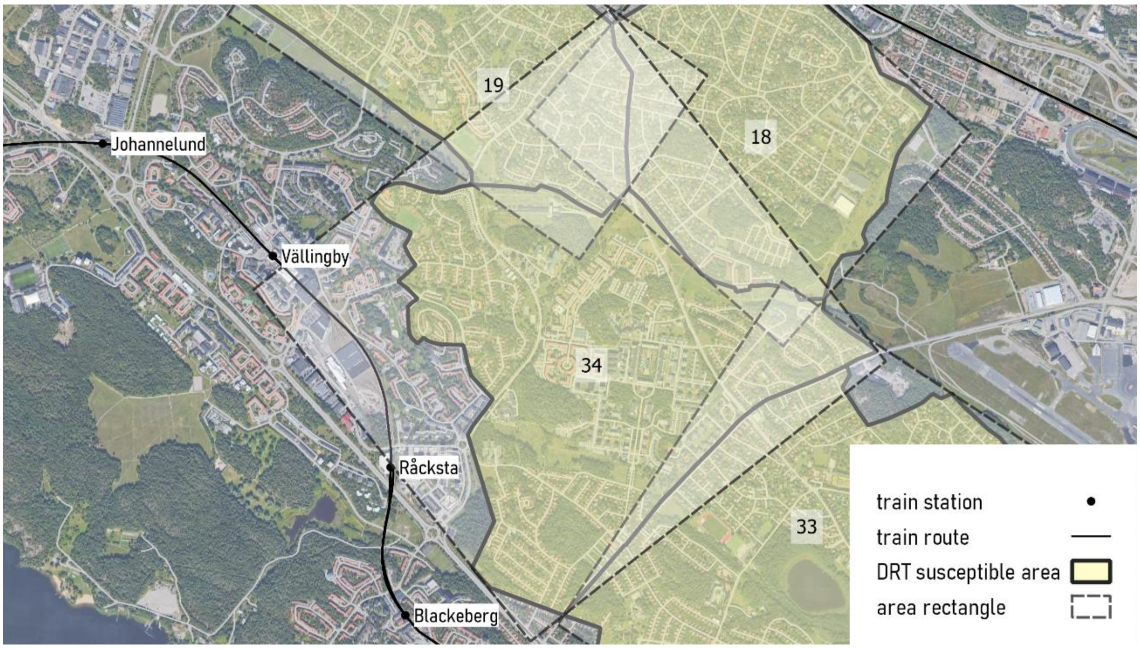
ZONE 33. Ängby - Bromma



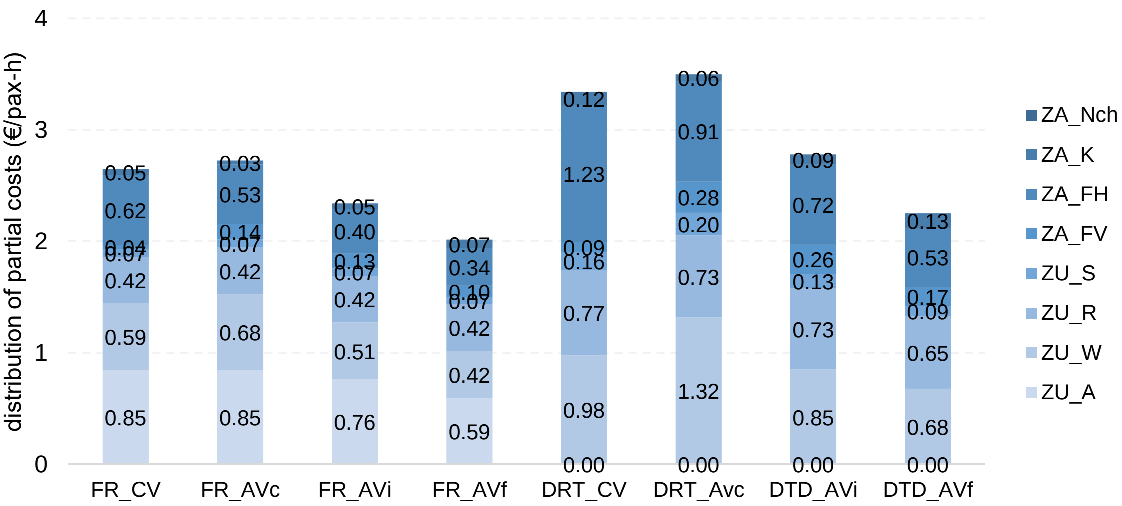
var	unit	input parameter	value
D_R	*(km)*	road length area to station	201.96
D_L	*(km)*	longitudinal dimension	1.77
D_W	*(km)*	transversal dimension	1.15
	(km²)	area	2.03
γ_r	-	route factor	1.3621
	(SEK/year)	household medium income	448262.37
VoT	*(€/h)*	value of time	8.64
	(pax/km²-day)	daily demand density	2092.11
	(pax/km²-h)	peak hour demand density	252.21
δ	*(pax/km²-h)*	hourly demand density	139.47
	(pax/h)	hourly trips	283.29



ZONE 34. Råcksta - Beckomberga



var	*unit*	input parameter	value
D_R	*(km)*	road length area to station	386.49
D_L	*(km)*	longitudinal dimension	0.99
D_W	*(km)*	transversal dimension	2.32
	(km²)	area	2.29
γ_r	-	route factor	1.9637
	(SEK/year)	household medium income	351767.82
VoT	*(€/h)*	value of time	6.78
	(pax/km²-day)	daily demand density	3258.34
	(pax/km²-h)	peak hour demand density	403.11
δ	*(pax/km²-h)*	hourly demand density	217.22
	(pax/h)	hourly trips	498.05



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